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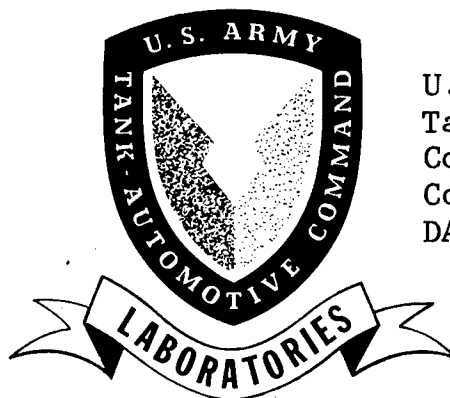
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TECHNICAL REPORT NO. 11768 (LL 144)

APPLYING FORCE FEEDBACK SERVOMECHANISM  
TECHNOLOGY TO MOBILITY PROBLEMS



U. S. Army  
Tank-Automotive  
Command  
Contract  
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by

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TACOM

MOBILITY SYSTEMS LABORATORY

U.S. ARMY TANK AUTOMOTIVE COMMAND Warren, Michigan

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AUGUST 1973

FINAL REPORT

by

Ralph S. Mosher

Prepared for the  
United States Army Tank-Automotive Command  
Mobility Systems Laboratory

Prepared by  
Robotics, Inc.  
Elnora, New York

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SUMMARY

The report summarizes force feedback servomechanism research performed under the sponsorship of TACOM, and the advanced Project Research Agency, with the purpose of defining and exploring possible new approaches in the design of mobility aids.

The fundamentals of manipulative man-machine control technology are reviewed. Factors contributing to effective bilateral servo design are discussed. Human factors related to force feedback controls are described. The development of a quadruped walking mechanism employing bilateral force feedback controls and spatial correspondence between operator controls and machine appendages is discussed in detail. A series of experiments with the quadruped test bed is described. Next a number of concepts are recommended where force feedback technology could possibly be applied to further the mobility of future Army vehicles. A section is devoted to a summary of transfer functions which represent pertinent servo systems and which lend themselves to the mathematical analysis of stability, gain, torque and other salient factors.

PREFACE

Surface mobility researchers have long been interested in investigating the walking mode of locomotion for possible vehicle application. Studies conducted in the Fifties indicated that controlling the "legs" while moving over rough terrain was the crucial problem.

This conclusion indicated that using man's superb neuro-muscular control system could provide the solution. The man-in-the-loop idea had already been successfully applied in the construction of very efficient and simple-to-operate manipulators. The key to these concepts was force feedback and spatial correspondence. As the result, a four-legged, 3,000-pound quadruped test bed was developed. The operator inside this device controls the four legs, each one being activated by his arms and legs. The mimic-like control system provides the operator with force information encountered or generated by the quadruped legs and since there is spatial correspondence between operator control and the end effectors of the four legs, working the machine is relatively easy. The control concept can be described as "cybernetic" because of the transmission of position and force information between the quadruped and the operator, and also called "anthropomorphic" because of the spatial correspondence or mimic-like control between the operator and the linkages of the quadruped legs.

Although at this time the idea of a walking truck is not seriously considered by the Army for practical application, force feedback servo-mechanisms remain the objects of active research because of their many-faceted potential in enhancing vehicle mobility and materials handling.

The purpose of this report is to describe force feedback systems and the results of walking machine experiments, to serve as reference material for the Army's mobility development work. This method of control can provide machinery with human-like action that mimics an operator's natural motions. In general, these special force and



position sensing servo-mechanisms show promise of providing answers to many control problems where man can take full advantage of his ability to detect forces and manipulate machinery in a natural way because it is easy for him to think of the machine as merely an extension of his own appendages.

Effectiveness of this control method was shown by a variety of maneuverability experiments. Human perception, judgment and agility are transmitted through the machine by means of special bilateral, force reaction, position control servo-mechanisms.

Recent technology history is characterized by the rapid and widespread application of automatic control, data processing, and information and control theory. In spite of the impressive mechanization achieved to date, one area of outstanding potential needs to be more fully exploited where the adaptive reflex control of man is transmitted directly to a mechanism. The quadruped test bed represents an excellent example of this type of control and its potential.

Many jobs require the sensing acuity of man, but are too difficult or the environment is too hostile to permit direct human participation. However, with spatial correspondence between operator/controller and responding output mechanisms combined with force feedback from the machine to the man it is possible to provide a man with machines that react to his natural neuromuscular reflexes. Heuristic analogies show promise of improving the fighting soldier's mobility through the use of these technical concepts.

To identify and prove the potential of this control concept where force feedback and spatial correspondence characteristics are used, the four-legged, 3,000-pound quadruped test bed is an excellent research tool. This four-legged, quadruped test bed with its twelve bilateral servo mechanisms is easily balanced and maneuvered by an operator. Without the force feedback feature reflecting forces encountered or generated by the quadruped to the

operator, the operation of the quadruped was impossible. This proves that spatial correspondence coupled with force feedback are needed in combination for control that will provide humanlike action. The experiment proved that this technology represents a unique capability. It is now a matter of fitting this research development work and its potential to the development engineer for his use in solving special mobility problems.

Force feedback research work has resulted in a certain expertise in man-machine control technology that can be brought to bear directly on many Army problems because machines which depend on operator control can be improved by making the man-machine relationship more effective.

### FORCE FEEDBACK MECHANISMS AS MOBILITY TOOLS

Compared to travel capabilities in the sea and air, advances in terrain mobility techniques are very slow and limited. The most significant reason for this is that the sea and air provide a predictable and consistent travel medium. Terrain on the other hand demonstrates an almost endless variety.

Because of the consistencies of sea and air travel conditions, ship and aircraft can be operated autonomously. This is not true for the travel of vehicles on terrain; man plays a very important role in the control and operation of the vehicle. Because of this, the man-machine relationships represent a crucial factor in perfecting mobility.

To advance mobility capabilities we must consider a basic question common to many other areas of technology: What is the most effective and beneficial combination of man and machines to improve vehicle mobility. Proper philosophy in the design of vehicles uses as its starting point man and his control activities and, then, moves from man to the considerations of manual and automatic devices as extensions of human control activities. This is in contrast with the practice of many vehicle designers who have created complex control mechanisms with very little regard to the psychophysical limitations and capabilities of the operator. Too often the designer has ignored, obscured, or treated casually the serious and difficult aspects of the vehicle control and man's subtle, mental and psychomotor capabilities. For off-road locomotion, sensing and information processing becomes a major operator requirement.

Tank tracks are tortured by scuffing and skidding, especially during turning, breaking and maneuvering. The performance characteristics of track-driven vehicles are limited by crude controls and by the "lack of communication" between the controls and the track. The ability of drivers differs greatly. Two basic reasons for this are: (1) extent of training, and (2) the innate ability of the

operator to overcome unnatural and incongruous control requirements. A common measure of operator capability is how well he can drive a tank up a steep and muddy slope without allowing one of the tracks to slip or hamper further travel. There are many reasons why man is needed in the control of machines. He is needed in the control system as a source of power, to employ his senses, for his reliability, his versatility and the simplicity of system design made possible by his inclusion, or for some combinations of these reasons. Proper man-machine relationships are important design considerations for control system design. Muscle power still has a role to play in control systems, especially when the nature of the system is such that man's presence is required anyway. The bicycle will remain an effective means of short trip transportation; and muscle power will still be used to operate brakes, steering, and gear shift on almost all Army vehicles of the future.

The engineering state-of-the-art has advanced much further with respect to the production and application of power than it has in the development of sensing instruments comparable with human senses. The thresholds of vision, hearing force, and position are remarkably low so that instruments of extraordinary sensitivity are required to produce performance equivalent to that of the operator. More important than the low thresholds of these senses is man's ability to recognize patterns and to distinguish signals from noise. This sensing capability is also augmented by the intricate human information processing capabilities.

The presence and function of an operator represents reliability, simplicity and versatility. Operating a complex military vehicle is an example of such a task. There is a trade-off between the simplicity of the equipment in a man-machine system and the simplicity of human operations the system entails. Human versatility contributes to systems' simplicity and reliability. Man may perform such a variety of functions in a system that his inclusion is justified even when such functions performed can be effectively automated.

In the case of off-road locomotion, operator creativity is a key function in the mobility problem. The human activity in the control system which would be very difficult to mechanize is human choice, requiring selection from alternatives in solving maneuvering problems. The operator's tasks then become one of translating the choice into physical events. These together comprise the essence of the process of control which is directed by the operator's sensing and creativity abilities. Automatic devices can help him evaluate the possible solutions but they cannot choose his goals and his criteria for him; the automatic device may simplify the physical events required of the operator to bring about the solution to the transport problem. Even so, the automatic function depends on the choice of the operator which makes him irreplaceable.

There are good reasons for attempting to perform as many tasks as possible by purely mechanical means. However, until such time as information and control theory and its associated technology match human capabilities in more than a few specialized fields, there is considerable opportunity for profitable symbiosis of man and machine. In these fields integration of man and machine in a system can be best characterized as solving interface problems. The communication between man and machine is so difficult that it is almost impossible to consider a truly integrated man-machine system. From an analytical point of view the transfer function for a man, except in the most simple cases, cannot be adequately expressed. As a result of these difficulties, the machine has been looked upon, in most cases, merely as an aid, a tool, for man. In trying to do as much by machine as possible, these difficulties have prevented the exploitation of interesting and profitable combinations of machines and men.

The quadruped test bed research program has provided a wealth of fundamental information that may help the development of better man-machine control technology.

This report is written for the purpose of delineating cybernetic anthropomorphous mechanisms and controls tech-

nology and also to define design guidelines for the development of new mobility devices that are now possible as a result of past research work. As mentioned before, this development work involved the manufacture of a four-legged, 3,000-pound quadruped test bed. This test bed is operated and controlled by an operator and special cybernetic anthropomorphous controlled mechanisms. This concept provided identification of basic psychophysical factors of human perambulation. From this information, interface problems between the human foot and the terrain have been identified. These in time can help the engineer identify design guidelines to enhance vehicle mobility characteristics in quite different applications. The program included very complete psychophysical operator characteristic studies. Prevalent factors included vision, vestibular sensing, tactile and kinesthetic force sensing, and proprioceptive position sensing. With the special control system designed for the test bed, an operator was easily trained to coordinate the multiplicity of human motions and forces needed to operate the quadruped test bed or vehicle. The operator's motions and forces were augmented and translated to the vehicle. The mimicked human motions produced locomotion and, most importantly, identified the basic human locomotion characteristics.

The test bed and approach to control provided an ideal method of identifying the very excellent off-road characteristics of perambulatory locomotion. This fundamental technology suggests a variety of machine types that would improve the mobility of the soldier.

Two salient control characteristics predominate this discipline: force reaction to the operator, and spatial correspondence between operator and power output mechanisms. These features provide the operator with a natural mental interpretation of the machine action and ability to respond instinctively and correctly in a natural manner by means of his neuromuscular reflexes. These features introduce humanlike reliability and capability to otherwise clumsy, crude and precarious machine operations.

Examples of possible applications of this general discipline of cybernetic anthropomorphous machine technology are:

(1) Manipulation of an articulated vehicle having two sections connected with a powered "universal joint".

(2) Extraction of a vehicle stuck in the mud; a force-controlled winch arrangement would prevent the operator from exerting uncontrolled forces which might damage the vehicle.

(3) The force balancing system could be employed to control the level of traction to wheels and tracks to minimize slip and optimize traction and decrease wear of the vehicle and decrease power requirements.

(4) Supply a dual wheel suspension system whereby a step-over-motion of one wheel over the other would provide a direct lift-out action instead of the usual plowing motion of a stuck wheel spinning in the mud. This concept is based on the powerful over-center kinematics of the human leg.

(5) The walking leg and animal sensing capabilities circumvent the antagonistic road resonance problems that many vehicles experience on rough terrain. The human brain identifies the terrain conditions ahead and adapts leg action to conform. It is suggested that it might be possible to provide a leading wheel, passive in terms of power but capable of monitoring terrain profile and reflecting this information to a powered suspension system. In turn, transient suspension characteristics could be generated to smooth the vehicle motion and avoid road resonance.

The powered suspension system would require considerable power under normal conditions. Successful use of this concept would depend largely on the ability to provide a semipassive suspension system where power is recirculated from one wheel suspension to the other with a minimum loss of power.

(6) Huge mine stripper shovels use large walking legs that are attached to the base of the machine and then operated to slowly move the shovel system to a new site. It is done this way because of the tremendous forces or loads involved and the ability to use this leg system for more than one machine. It is suggested that portable leg systems could be carried on a mission to be used for vehicles bogged down in soft soil. The legs could be attached to the vehicle and operated to "walk the vehicle out".

(7) An articulated utility boom controlled with hydromechanical bilateral servo mechanisms would allow untrained soldiers to do intricate tasks very efficiently. Examples would be clearing debris off the road, scanning the road with a mine detector and using the boom as an aid to help solve mobility problems of other vehicles. The boom could be used to handle any tow cables, logs and beams that might be needed for bridging a crevasse. In addition, the boom could be equipped with an end effect as suited to load ammunition boxes or other cargo.

It is hoped that this unique control system developed will be the harbinger of many new mobility mechanisms. The closely coordinated man-machine system concept is new in terms of identifying appropriate human psychophysical factors and applying them to appropriate machine concepts. As a result, control systems are being perfected that can transmit adequate information between the man and the machine, the required information allows the man to exploit the union of his superbly integrated sensory system with the large power potential of machinery.



## HISTORICAL BACKGROUND

As early as 1947, robots and supporting technology development work became very popular because of the impetus of the atomic energy program. This was the beginning of the first sophisticated robots or manipulators that could effectively project man's manipulative capabilities to a work site remote to the operator.

It was discovered through a series of development stages that the control characteristics of a multimotion manipulator must have two basic ingredients in order to effectively project the man's capabilities through the robot. They are spatial correspondence between master and slave, and slave force reflection to the operator. These two ingredients are provided through the use of bilateral force-reflecting position servo-mechanisms. With this control method, the operator has the ability to manipulate a multitude of motions simultaneously by means of complete spatial correspondence between the master control and the slave end effector and the ability to interpret forces generated or encountered at the slave end effector. Through the years the characteristics of these servo controls were improved to provide natural human input/output characteristics that allow duplication and amplification of human psychomotor skills. There is a whole family of second-order characteristics which are very important with regard to proficient man-machine integration. Development of variations of control technology have resulted in improvement in these characteristics. The section titled "Force Feedback Mechanism Technology" describes these characteristics and their importance in detail.

A great deal of the original manipulator technology development work was done at the Argonne National Laboratory and directed by the late Raymond Goertz. It is interesting to note that the first manipulator developed was a simple all-mechanical, connected, master-slave system where the connections between the two stations were made by linkages passing over a protective wall.

This was possible at that time because of the low radiation level. This simple all-mechanical master-slave manipulator provided the necessary control characteristics mentioned above. The manipulator provided true spatial correspondence between master and slave for the multiplicity of motions involved and also reflected forces encountered or generated. In 1954, Raymond Goertz built an electric master-slave manipulator incorporating servos and force reflection. The master-slave position control of the manipulator arms and hands with force reflection made this the first bilateral electric servo-manipulator ever built. The separation of the mechanical master and slave stations by the servo mechanisms required special servo control innovations to provide the particular set of information transfer characteristics. This was needed to provide adequate information processing between the operator and the slave station.

Very interesting research of walking vehicle concepts were being pursued about the same time. The similarity in the two development programs was that the first approach was to use all mechanical linkage systems, and then apply the control technology developed for the remote master-slave manipulator systems. The logical explanation for the common results in both the manipulator and the walking levered vehicle was that both had to work with and conform to a variety of shapes and sizes of material. Of course, the manipulator handled a variety of radioactive material and tools whereas the walking levered vehicle was required to traverse over a variety of terrain profiles.

In 1957 Professor Shigley of the University of Michigan undertook the task of finding a linkage that would provide straight-line motion of the foot and reduce inertia forces to a minimum. This work was performed under Army sponsorship. After considerable study and the construction of a model, it was concluded that the straight-line mechanical linkage machine was not practical and this approach was abandoned.

As a result of this study work, the solution of the control problem identified appeared to be a sensing and computing system that is comparable to the neuromuscular

control ability of an animal. Duplicating animal control mechanically, however, is not practical. The conclusion was obvious that even if we overcame the mechanical problems, the walking machine was not practical until the simple means of control became available. Results of manipulator development work at the time had proven that the solution to the control problem was practical. The control system developed for the master-slave system by Raymond Goertz was the approach that made the development of a walking levered vehicle feasible.

In 1963, Robert A. Morrison of Space General Corporation developed an eight-legged walking machine for the purpose of transporting crippled children over irregular terrain such as stairs and street curbs. The eight legs of this device operate as four pairs in a sequence that keeps four legs on the ground at all times for the sake of stability. These electrically-actuated automatic walkers have successfully demonstrated their feasibility. However, their proficiency is poor. Good walking machine performance depends on master-slave type of control which would allow capable negotiations over random terrain conditions.

At the General Electric Company in 1958, the author and his co-workers developed a master-slave robot called "Handyman". It is similar to that of the one developed by Argonne National Laboratory except for two basic differences: instead of electro-mechanical servos, the General Electric Company used electrohydraulic servo control and the hand had four degrees of freedom providing prehensile grasping ability. This equipment was built for the joint AEC-USAF Aircraft Nuclear Propulsion Program. (See Figure 1.)

Essentially the manipulator consists of a pair of mechanical arms and hands in roughly human form that are connected electrically to a harness worn by the operator. The system causes the mechanical limbs to mimic the actions of the man's arms and hands (that is, to follow the human template), while the man, in turn, receives signals from the machine conveying information about force and position. Thus, the machine is coupled to the man's sensory and motor

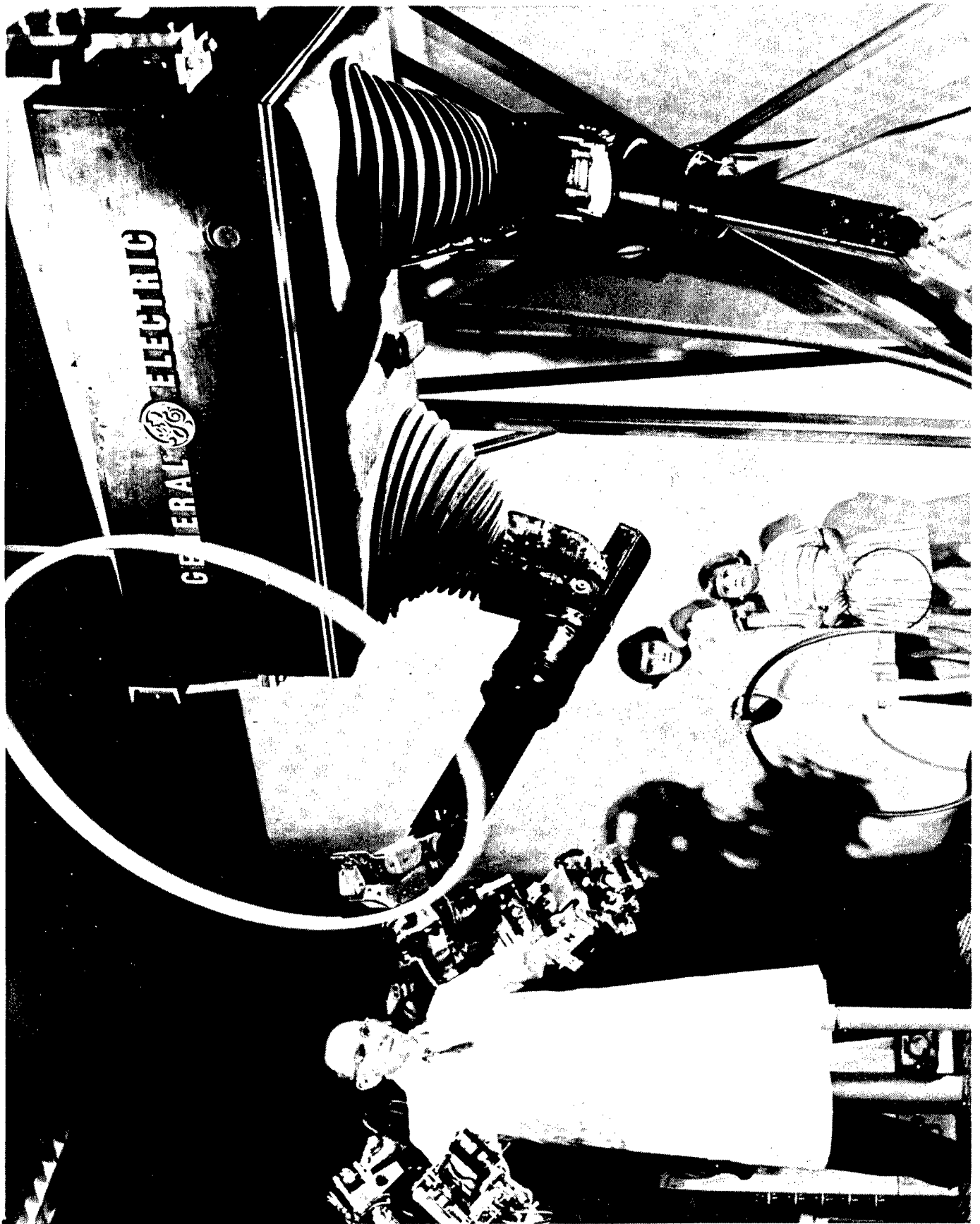


Figure 1    Hula Hoop - Handyman

system in such a way that the whole setup operates in a highly integrated manner through feedback loops.

Handyman has ten motions in each arm, actuated hydraulically by means of electric signals that cause the arm and hand to carry out precisely the same motions as those made by the operator as indicated by his finger and arm angles and other physical signs. The machine, in handling an object, registers the positions and forces associated with the manipulation; this information is translated into electric signals and sent back to actuators attached to the operator, which convey to him forces proportional to those experienced by the machine. The harness the operator wears is called a follower rack.

The coupling is so direct and detailed that the man does not have to think about operating the machine. He simply concentrates on the manipulation task itself, and he observes the actions of the mechanical arms and hands as if they were his own. (A prediction of a means of control for walking levered vehicles.)

Experience in the design and use of Handyman (which was created originally for remote-control work with radioactive materials) has shown that a wide range of variations of this prototype machine is feasible. The design can be varied in size (producing very large or very small Handymen) and in many details. The topological relations between the machine and the operator must, however, be kept the same so that he does not lose mental contact with the mechanical arms which mimic his behavior.

The Handyman experience has also brought to light several critical design requirements for such a machine. It must be free of any internal forces (such as friction, dead weight or the like) that would tend to tire the operator or mask the forces he is trying to measure. The machine's information about force and position must be reflected to him firmly and crisply so that he can work at the speed he desires, maintain smooth control of the velocity of the machine's movements and conduct those movements without overshooting or oscillation. The amount of force reflected back to the operator should be directly

proportional to that experienced by the machine. The proportion should be set at a level such that the force is strong enough to provide clear signals, but not so strong as to tire the operator when he has to work with the machine for any length of time. The design should make the nature of the force unambiguous; for instance, when the robot hand grasps a ball, the signal coming back to the operator should tell him whether it is from the ball being squeezed or from the fingers which are being pressed together.

In 1964, Neil J. Mizen of Cornell Aeronautical Laboratories developed a complete passive mechanical exoskeleton to be worn by a man. This was done in anticipation of being able to develop a powered exoskeletal device that would enable the man to wear the equipment and amplify his strength so that he could pick up as much as 1,500 pounds, and walk and manipulate with this load. This work was sponsored by the Air Force. The conclusion of this work was that a man could be incased in an exoskeleton device and retain total body freedom to move about and do useful tasks without discomfort. Under joint sponsorship by the United States Navy and the United States Army, the General Electric Company was contracted to continue this work. Their objective was to build a powered exoskeletal device that would enable a man to lift 1,500 pounds six feet high and carry this load 25 feet in ten seconds. The General Electric Company is currently working on this program, and although some of the required servos still present problems, there is no doubt that a powered exoskeleton can be constructed enabling a man to perform these operations. This exoskeletal device has 28 servo mechanisms and has the operator, the master and the slave in juxtaposition. This system is very complex, and more development work is needed to make the concept practical.

Essentially, the exoskeleton is a walking machine that is balanced and walked by the operator's natural walking motions, which are the controlling elements. The master next to the operator takes the operator body signals and directs the powered exoskeletal device to walk in similar fashion.

In this application there is very little room between the master and the slave which causes severe technical problems in the servo design. Similar research work is being done in Germany by Professor Dr. Ing. Hanns Kleinwachter. (Professor Kleinwachter's address is Deutsche Bank #245068, Lorrach, Germany.) His work is sponsored by the German government, and it involves developing an exoskeletal device much like the one previously described. The objective of their work is to develop prosthetic devices as well as remotely-controlled walking robots which could possibly be used for rescue work or to clear away debris caused by nuclear accidents or bombing.

In 1961, a General Mills Model, #150 manipulator (designed to handle nuclear material), was installed on the U.S.S. Trieste with the purpose of doing deep sea research work. In 1963 the United States Navy began several deep submergence projects, which included the development of underwater manipulators.

Case Institute of Technology, in 1966, demonstrated the ability to computer-control a manipulator that could perform programmed routine operations. This work was sponsored by NASA. Widespread research work has been done to perfect a variety of special controls that will let a man drive machines in humanlike fashion.

This new level of awareness in man-machine control technology can be applied to other fields of work. A natural target for new applications is Army transportation vehicle methodology where an operator is involved. Can the mobility of the Army be improved by designing better man-machine operator control techniques?

To search and define appropriate man-machine control parameters related to Army vehicle control, a walking levered quadruped test bed was developed as a research tool by the General Electric Company. The controls possessed cybernetic and anthropomorphous characteristics. Hydromechanical servo components were used in anticipation of the need for rugged controls for Army use.

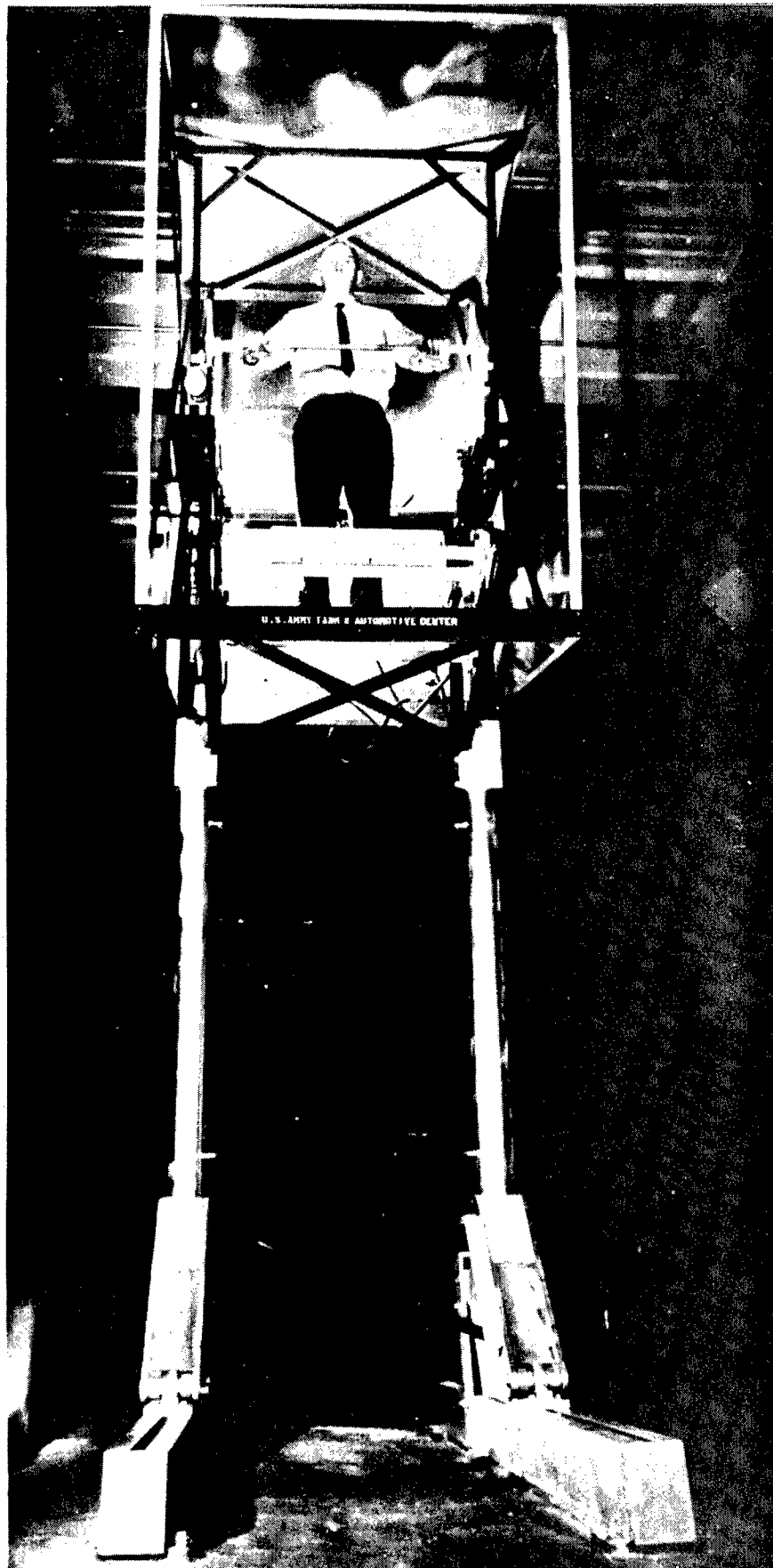
The first step, a feasibility study of a walking levered vehicle, was based on the use of controls perfected for manipulator use. A basic question behind this program was the identification of the many subtle human factors and mechanical parameters that make a man so effective in maneuvering through and over all kinds of terrain conditions. It was expected that this research work would lead to design guidelines for the establishment of vehicle characteristics and operator control techniques.

Psychological studies proved that the walking machine was feasible. The next step in this program was to build a very large machine to prove that man can balance the machine and that servos could be perfected to provide the proper information and control capability. This experiment proved conclusively that the servos were adequate and that the operator could balance such a machine easily (Figure 2).

The encouraging results from this balance experiment were followed by a program with the objective of developing a four-legged 3,000-pound quadruped test bed that would be operated by a man inside the machine using the basic controls developed for the balance experiment. This machine was built and tested with results that were very encouraging and dramatic. Not only could the man balance and operate this test bed, but he could also do many very challenging maneuvers with no difficulty at all. The machine is truly anthropomorphous and human-like in its response characteristics. The operator is strapped into the quadruped test bed and operates all twelve servo mechanisms simultaneously to balance the machine and maneuver it to do certain trial tasks. The quadruped test bed proves that force feedback control technology is very powerful and unique. It is now up to the engineer to put these tools to use to devise better mobility control techniques (See Figure 4).



Figure 2 Balance Experiment



FUNDAMENTALS OF MANIPULATIVE MAN-MACHINE CONTROL TECHNOLOGY

In recent decades self-controlled machines and self-controlled industrial processes have evolved rapidly, but there are still many tasks that resist the elimination of the human operator. Tasks that will do so for a long time to come are ordinary manipulation of highway or off-road vehicles and hand tool work.

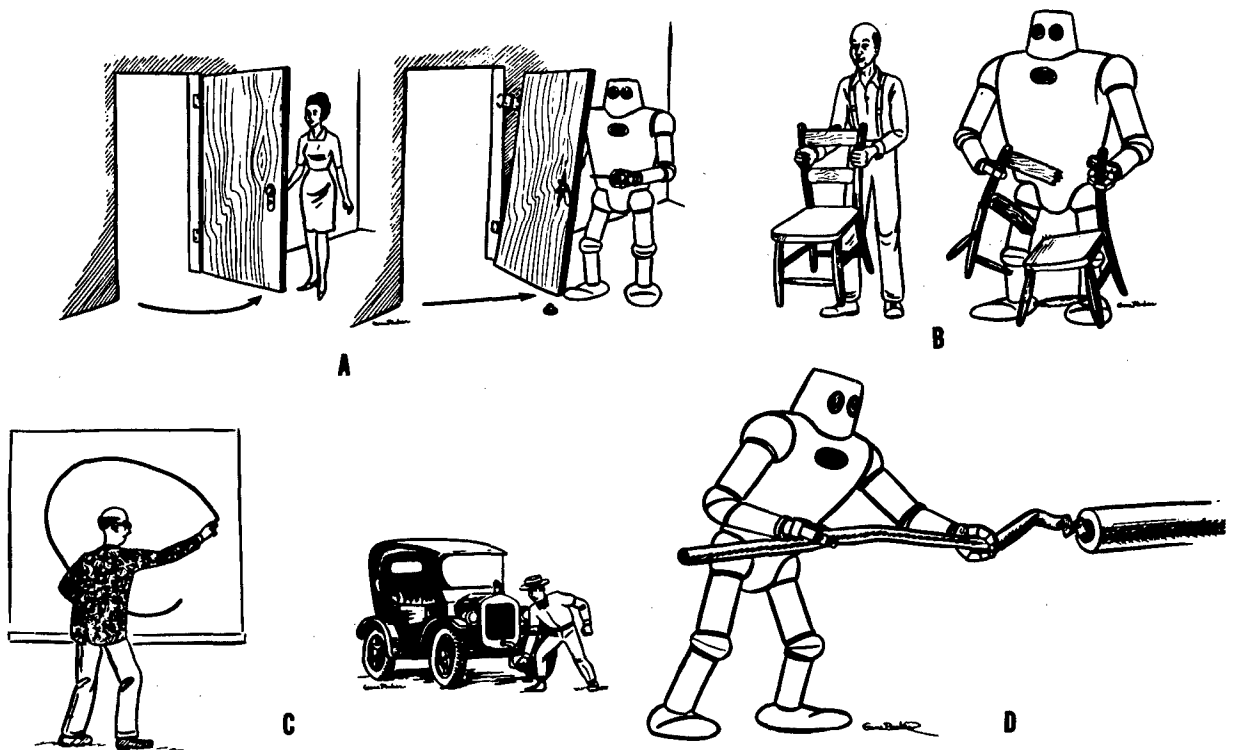
An automatic machine can be almost entirely self-sufficient in a mass-production process. There the problem is to carry out programmed, repetitive operations under more or less fixed conditions. But consider the operations that must be performed by a power shovel or a crane. In digging an excavation or transporting objects from one location to another, the machine is called on to make continual adjustments to changing conditions. For this it requires a human operator applying human information and control. There exists neither the technology nor the hardware to replace that control system with an artificial one, and if such hardware existed, it would be fantastically expensive.

On the other hand, the coupling of a machine to human control can be developed to far higher levels of refinement than the rudimentary and clumsy operations of power shovels, cranes or vehicles. There are forms of manipulation which require all the delicacy of a human operator but cannot be performed by man unless he is assisted by a machine. Among these are operations that call for super-human strength and those that must be performed in a hostile environment such as the highly radioactive interior of a "hot chemistry" laboratory or a nuclear reactor. The need for handling radioactive materials by remote control has been mainly responsible for the invention and design of a variety of artificial manipulators.

There are now manipulators for handling microscopic objects (micromanipulators), for handling explosive chemicals, for working underwater and for certain industrial operations.

## PSYCHOPHYSICAL FACTORS

Manipulation is a much more complex activity than it appears to be. One must begin, therefore, with a detailed analysis of the elementary motions and factors involved in any sort of manipulative performance (see Figure 3). Consider the seemingly simple operation of opening a door. One grasps the doorknob and swings the door in an arc of a circle with the hinge axis at its center. The hand pulling the door must follow an arc lying in a plane at the level of the knob parallel to the plane of the floor, and it must conform to the circumference of the circle defined by the distance from the knob to the hinge axis. In doing this, the hand, assisted by the human nervous system, is guided by the door's resistance to being pulled along any other path. In other words, the human motor system responds to a feedback of forces that must be



- A. Lacking Human Sensing, Robot Snaps Door but the Girl Complies
- B. Lacking Human Sensing, Robot Shatters Chair
- C. Crank Handle Forces Perfect Circular Pattern and Chalk does not
- D. Lacking Human Sensing, Robot Jams and Bends Pipe

Figure 3: Opening door and other "difficult" tasks.

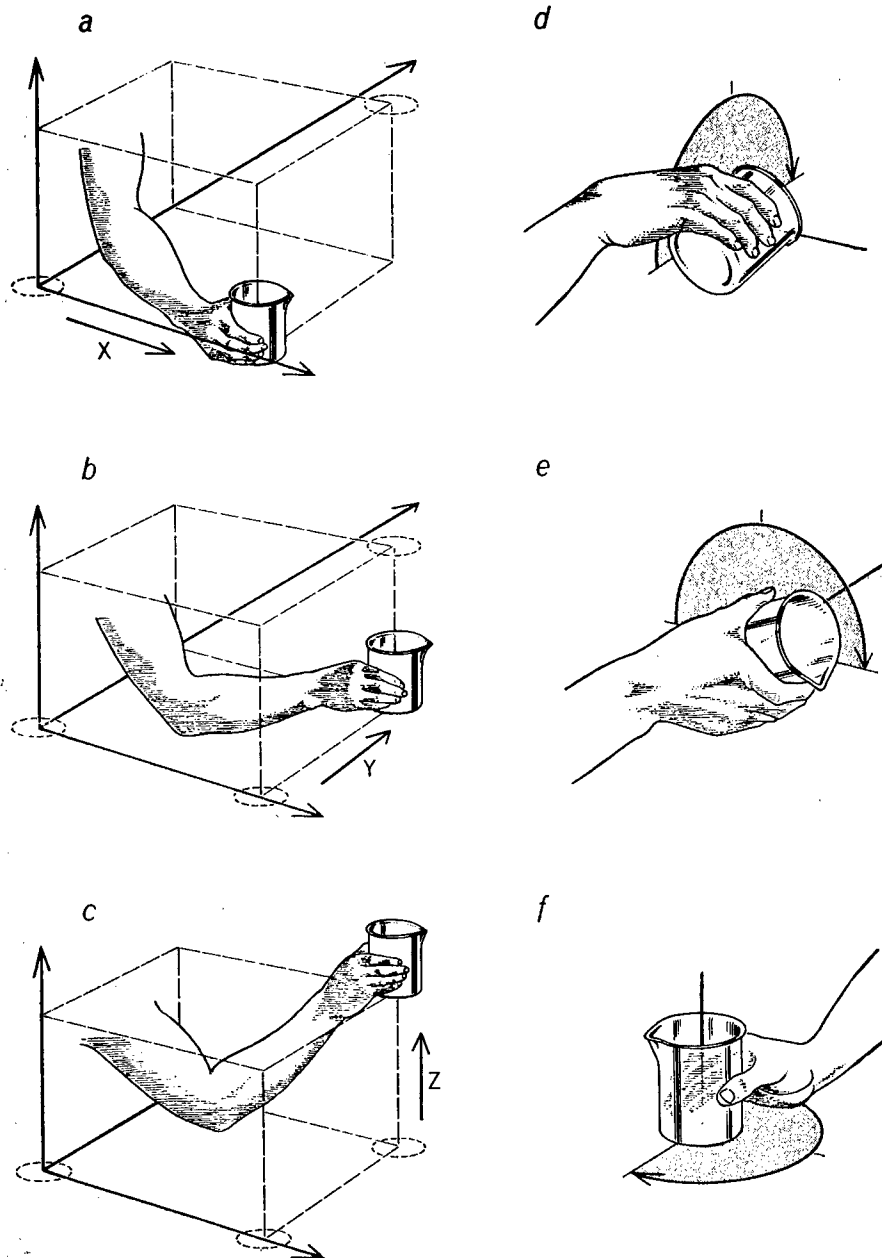
interpreted. A strong robot, lacking any means of such interpretation and free to pull in any direction, might easily pull the door off its hinges instead of swinging it open. Similarly, the same robot, given a chair to carry, might pull it to pieces because of inability to sense or interpret the resistance of the chair's structure to being pulled apart. Consider another example: The problem of sliding a rod into a tube into which it will just fit snugly. A man can do this even blindfolded by trying various angles of insertion until he finds the one at which he can push the rod in without forcing it. A robot, on the other hand, would simply push hard at any angle and bend or crumple the rod.

The factor involved here can be illustrated in another way. As everyone knows, it is virtually impossible to draw a perfect circle freehand. The senses of vision and touch are not sufficient guides to perform this operation accurately. Yet, anyone who turns the handle of a pencil sharpener or an eggbeater describes a true circle in the air every time. The handle provides the guide, and the combination of tactile and kinesthetic force and proprioceptive position sensing are called into play and the body's skeletal and muscular system complies to this guide.

It follows, then, that one of the main requirements for a mechanical manipulator is that it must be able to transmit kinesthetic force and proprioceptiveness, corresponding to the same human senses. It must be capable of detecting changes of force and position, large or small, and transmitting this information accurately to the human operator. Such a device, possessing the properties of feedback and kinesthesia, can be described as a cybernetic anthropomorphous machine.

The next primary requirement for a manipulator is a quasi-human repertory of motions. (See Figure 4.) In our essentially Euclidean world it takes six degrees of freedom of motion to position an object: three to place it in space (as defined by the three familiar coordinates  $x$ ,  $y$  and  $z$ ) and three to orient the object itself (in the attitudes known as pitch, roll and yaw). A machine can easily be designed to carry out the various necessary

**Figure 4      Beaker**



**TWO SETS OF MOTIONS** constitute the six degrees of freedom for any object in space. **Direct motion** along three coordinates determines position: the beaker is moved forward (a), sideward (b) and upward (c). Three coordinates of rotation determine the object's **orientation**: pitch, or elevation (d); roll, or twist (e), and yaw, or azimuthal rotation (f). Any manipulator must make these six motions if it is to simulate human arm movements.

movements, but if a system of levers, switches or buttons were used to control these motions, the human operator would have to operate six controls simultaneously. A man cannot accurately operate more than two controls at a time. Therefore, an effective manipulator must be coupled to the operator more directly than through devices such as levers or buttons.

QUALITATIVE DEFINITION OF  
CYBERNETIC ANTHROPOMORPHIC CONTROL TECHNOLOGY

A number of very significant advantages accrue from incorporating cybernetic mechanisms in mechanical operations where a reciprocity of information is transmitted between operator and his machine.

(1) Switches, levers, pedals and similar apparatus are eliminated. As an example, a walking levered vehicle would not require transmissions, brake pedals, or clutches.

(2) An operator can do more things because of increased machine versatility.

(3) Very little training is necessary for an operator to gain a high level of proficiency because the machine mimics natural human motions.

(4) There is less chance of damage to either the task object or the machine itself because of force interpretations provided to the operator.

(5) All task programming equipment is eliminated.

(6) With the machine responding to the operator in human-like fashion with extreme versatility in agility and dexterity, the operator's problem-solving capability can be reflected as physical "answers" through the response of the machine. This is an increase in capability as compared to our on-off controlled machine.

Effective integration of man and machine can only be achieved when the operator's natural information and control capability is brought into precise correspondence with the machine's motions. A variety of manipulator systems successfully employing this correspondence have already been developed and proved to be very effective provided this accurate integrity of control is maintained.

## Master Station

The cybernetic control method requires an exoskeletal master station that has precise spatial correspondence with the operator. The fixed kinematics of the master control must be attachable at critical points to the operator's appendage and therefore must provide freedom of motion that will easily comply with the biokinematic motion of the operator's arm or leg. With the proper mechanical design, the forces generated or encountered at the slave station can be reflected to the exoskeletal control and at the same time retain force vector spatial correspondence. It is very important that forces encountered and generated at the slave end are readily and accurately interpreted, so that the operator can react with his natural neuromuscular sense of control with the assurance that the slave manipulator will respond in a natural and desirable manner.

Except for the case where the master station has redundant motions in the controls (i.e., two or more motions with coaxial axes), the necessary operator attachments are confined to the hand and forearm section. These basic design guidelines apply to leg and foot controls also.

Consequently, the exoskeleton need not be one to one in size compared to the man nor in precise juxtaposition with the operator's controlling arm. To accommodate limited master control operating volume and a minimum force system, the ratios of position and force from master to slave can be optimized without complicating design or hindering operator effectiveness. For example, the force ratio could be 4:1 where the operator feels one-fourth slave force. Likewise, the master control arm could be one-fifth the size of the master so that a movement of one foot length by the master reflects five feet travel of the slave. Except for special cases of limited variation, similarity in kinematic geometry must be maintained. Deviations in orientation of the master frame of reference with respect to the corresponding reference of the slave is a critical factor. Some deviation can be accommodated without difficulty. As a general rule a  $45^{\circ}$  variation is acceptable and  $90^{\circ}$  is very undesirable.



## Manipulator Arm Design

It is not for lack of design imagination that the manipulator is patterned after the human arm. Rather, it is because of technical appreciation of the effectiveness of human morphology or biomechanics. Human wrist and elbow joints are most proficient at maneuvering through openings and around objects. The engineer seeks to achieve a similar degree of proficiency in the manipulator arm. The size and dexterity of the arm depends largely on the work requirements and on restrictions to maneuverability imposed by the peripheral equipment.

## Terminal Devices

It is imperative that the terminal device perform well; otherwise, the manipulator is worthless. "Hand" designs range from a simple hook or vise gripper to a complex, articulating mechanical hand with prehensile grasp. Special tools can be attached to supplement terminal device versatility. They can be designed to be interchangeable with others or can be replaced by special purpose tools, such as impact wrenches, hammers or cutters.

## Servo System

The force-reflecting servo components must be efficient, reliable, small and impervious to the hostile environment. They require good overhauling characteristics and must permit an easy, freewheeling effect for the operator as he directs the master through its manipulations. They must be capable of reflecting forces accurately. Force information, sensitivity, and resolution must be crisp and clear. Most important of all, force reflection must be drift free or unbiased. A biased force would deteriorate force sensitivity and cause operator fatigue.

The bilateral servo designed for manipulators has three very special design characteristics: viscous drag, stability for various mass loads, and force drift.

Viscous drag prevents good overhauling characteristics. Viscous drag is represented as a force proportional to speed

and a deterrent that the operator feels as he attempts to swing the master control through space without a load at the slave end. The viscous drag can be controlled to an acceptable minimum by proper servo circuit design. These design approaches are identified in Section 13 of this report.

Servomechanism stability for manipulators is an unusually difficult problem. When the mechanical hand lifts a large load or touches a floor or wall, the load mass approaches infinity. Variations of load size on the slave end and operator hand-on and hand-off the master control also represent variations of effective inertia to the servo system. Inertia reflected to the servo system represents a sensitive variable to the stability transfer characteristics. The gain of the servo system is required to be high to keep viscous drag down and force sensitivity up and yet high gain represents instability problems. Because of this, bilateral servos almost always require special "RC" (resistor-capacitor electrical network) compensation stabilizing networks and, in some cases, tachometer or velocity feedback is needed.

The third key characteristic problem in the bilateral servo is force drift tendencies. These drift problems are usually minimized by particular servo circuit techniques and drift compensators in the electronic amplifiers and electrohydraulic servo valves.

Another set of erroneous forces that must be avoided are caused by the actual weight of the slave and master arm system. If the slave arm reflects forces encountered or generated, it naturally follows that it will also reflect a proportion of its own dead weight. This must be compensated for by appropriate counterweighting either through servo system techniques or springs or counterweight compensations.

#### Other Factors in Bilateral Servo Design

The system must be stiff to give the operator a crisp feel. The measure of stiffness is called compliance and is measured in radians per inch. The smaller the number is the higher the force resolution will be. Servo loop

gain must be raised to reduce this compliance factor. A second factor that is closely related to compliance is called slew error. This error refers to the amount of desynchronization of slave to master caused by rapid traverse of master and phase lag of the following slaves. The next parameter that is important is the overhauling characteristic which can be defined as force threshold. In the manipulator, all mechanical linkages must be designed so that they can be caused to move by forces impinged on either end of the linkage train. A simple linkage system represents this requirement, whereas, a worm and wheel does not. Also, certain servo system circuits cause more slew drag than others.

With the slave forces reflected to the operator, one can expect that frictional forces in the slave would be reflected also. Friction forces or power components that are inefficient will reflect a certain level of residual force back to the operator which is completely independent from the forces associated with doing a task. The force level caused by such errors will deter the sensitivity of the system in regard to interpreting small forces generated at the slave end.

Total linkage systems in series can cause quite a bit of backlash in the system. Not only will backlash tend to cause instability of the servo, but it is also disconcerting to the operator to have this dead band of motion without any responding force or position following of the slave.

In general, it is very important that the servo system parameters be well defined in designing a bilateral system for human control. There must be an understanding of the human biomechanics, the psychophysical factors, and the complex technology of servo systems mechanical engineering. The parameters must be well proportioned, relative to each other in order to achieve success in combining man and machine effectively.

#### Resistance in Control Devices

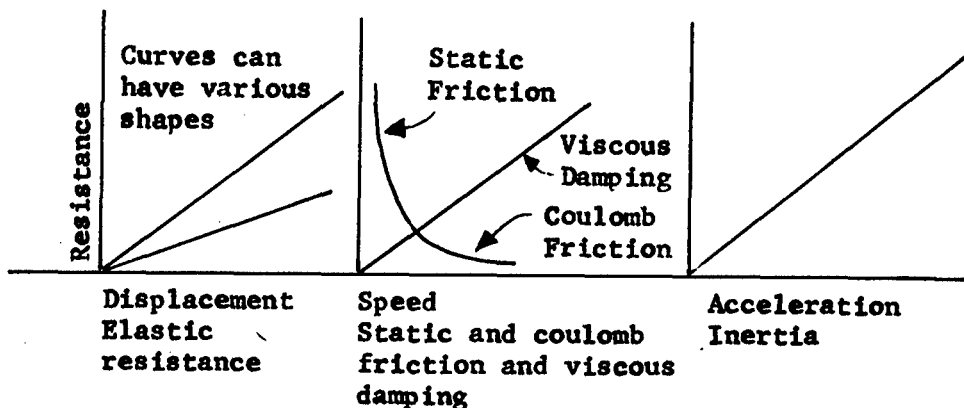
All control devices offer at least a slight resistance to their activation or operation. Performance of the control devices can be affected by the type and amount of

resistance. It is possible, however, within reasonable limits to so design control devices that specified resistance characteristics are built into the devices. In view of this possibility, a brief look at human performance under different types and amounts of control resistance is in order. In this connection, the resistance of control devices not only interacts with the execution of physical force applied to a device by a body member (such as a hand or foot) but also affects the nature of the feedback which the operator receives in using the device.

### Effects of Resistance on Performance

The primary types of resistance in controls are elastic resistance (as in spring-loaded controls); viscous damping (a force opposite to that of input, proportional to output speed); static and coulomb friction; and inertia. Illustrations of these are given in the following sketches:

Figure 5: Type of Resistance in Controls



The effects of various types and amounts of resistance on the use of control devices are only partially known, and, in fact, there are some conflicting bits of evidence that have not yet been fully resolved. To complicate matters, there seem to be some interactions among the various sources of resistance.

It probably can be said, however, that - with one possible exception - static and coulomb friction tend to cause degradation. This is essentially a function of the

fact that there is no systematic relationship between such resistance and any aspect of the control movement such as displacement, speed or acceleration; it can thus not produce any meaningful feedback to the user of the control movement. An exception is related to the possible advantage of static friction in preventing accidental activation of a device due to bumping against it, jarring, hand tremor, etc.; if the amount of such resistance is sufficient, it is possible to rest the body member on the control without activating it.

### Controls and Related Devices

The effects of the other types of resistances have been investigated in different studies, including one study that dealt with all three types, namely, elastic resistance, viscous damping, and inertia. One phase of this study was concerned with the effects of feedback from these types of resistances on performance. In this, subjects performed simple circular and triangular control motions with a joy stick when the control was loaded with varying degrees of spring stiffness (elastic resistance), damping and mass (inertia).

The study was concerned with the testing of the following hypotheses, based on the nature of the type of feedback that would be possible from the three types of resistance studied: (a) that accuracy in use of moving controls would be improved by increasing the elasticity of the control (since elastic resistance is related to displacement which can be perceived in space visually); and (b) that accuracy in maintaining a prescribed rate of movement would be improved by adding viscous damping or by adding inertia (since damping and inertia resistance are related not to displacement but to speed and acceleration respectively). The second of these hypotheses was supported by the study; there was greater uniformity of speed under increased damping and under increased inertia conditions than when these were minimal. The first of these hypotheses was not supported; spring loading (adding elastic resistance) did not significantly improve spatial accuracy (the accuracy of the movements made). As suggested by the investigators, however, this might be because longer training might be

necessary for such effects to become evident.

As implied above, however, the conditions and circumstances under which the different types of resistances improve performance, or bring about degradation therein, cannot yet be specified. For example, inertia does not invariably improve performance. This was indicated by the results of a study in which inertia was added in the form of flywheels to the shaft of a knob. The addition of one, two, three, or four flywheels had little or no effect on either travel or adjust time (in setting a pointer by use of the knob control), except when heavy friction was also added to the system. With heavy friction, inertia tended to aid performance, presumably because it compensated in part for the friction drag.

#### Force and Amplitude as Feedback Cues

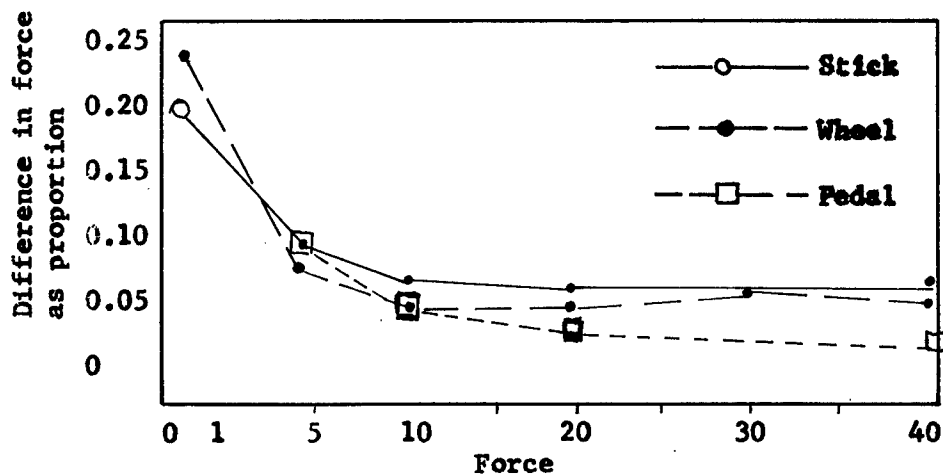
As indicated above, the force which is required to overcome the resistance of a control device can provide useful feedback cues. Such cues are sensed largely through the tactile (touch) sense. On the other hand, the amplitude of movement (say, of a hand, arm, or foot) is sensed through the kinesthetic sense (from the proprioceptors in the muscles and joints).

#### Ability to Reproduce Force

Where force is used as a cue, the operator needs to apply what he considers the right amount of force to the control. But how well can people reproduce a previously experienced force? And do such judgements vary with the amount of the force to be overcome? In a study designed to answer these questions, the subjects operated three kinds of controls, namely, a stick, a wheel (as in an airplane), and a pedal (like the rudder control in a plane). These controls were so designed that varying degrees of pressure (force) could be exerted with very little movement of the control device itself; they were pressure-types of controls involving elastic resistance but little actual displacement.

After some training and practice in "reproducing" various forces, a series of trials was attempted by each subject

(20 for each control, except with the pedal, for which 15 trials were used). Measures of actual pressure exerted were then compared with the pressures that the subjects attempted to reproduce. The difference in limens by pounds of pressure for the various types of controls are shown below. Since the difference in limen is the average difference that can just barely be detected, two pressures have to differ by an amount greater than the limen in order to be detected as being different. In the case in question, it is shown as a ratio, specifically the proportion of the standard pressure (the one to be reproduced) that can barely be detected.



**Figure 6 Operator Force Detection**

#### Controls and Related Devices

Since the curves for the three types of controls are so similar, the same conclusions seem to apply to all of them. It can be seen that the limen drops off markedly between 6 and 10 lbs., and that it becomes relatively constant beyond that. In more practical terms, the results mean that in attempting to reproduce pressures under about 5 lbs., or possibly 10, the errors are proportionately greater than they are for heavier pressures. If differences in pressures are to be used as a basis for judging the operation of control devices, the pressures used preferably should be above 5 or 10 lbs., in order that more accurate discriminations can be made. For pedal controls especially,

they should be above this limit because of the weight of the foot. The experimenter suggested that, if varying levels of pressure discrimination are to be made, the equipment should provide a wide range of pressures up to 30 or 40 lbs. Beyond these pressures, the likelihood of fatigue increases as well as the likelihood of slower operation.

### Comparison of Pressure with Amplitude Cues

Where both pressure and amount of amplitude (displacement of the control) can provide feedback, it would be useful to the designer to know the relative usefulness of one or the other (singly or in combination). The evidence regarding this, however, is not entirely consistent.

It is evident, from experience gained during our research program, that there are still some missing pieces of this jigsaw puzzle. In sifting some of the evidence, however, a few points seem to be warranted. It seems that there is no clear and consistent superiority of one mode of feedback over the other, suggesting that they both may have usefulness in control devices. Further, it seems that where distance of movement is limited, pressure cues are especially useful guides to the appropriate control of control devices. There is no evidence (within reasonable limits) that either type of feedback, in combination with the other, affects performance adversely. The reference by pilots and other vehicle operators to the "feel" of a control device implies desirability that way.

### System Time Lags

Virtually inherent in any man-machine system is some lag or delay in the response to a changed input. This lag generally can be viewed as consisting of two components, namely, lag in the system itself and human reaction time. In practice, however, these certainly interact.

### System Lag

Lag in a system can occur between various sequential functions, and it can be of different types. For example,



there can be a lag in information being fed into an input display; thus even in TV transmission there is a lag (although very slight) between the transmitter and the TV tube; in transmission to and from the moon there is one-way lag of a bit less than  $1\frac{1}{2}$  sec. Perhaps more frequently, however, system lags occur between an operator's control action (with some control device) and the corresponding response of the system.

Since the lag in a system is in part a function of the mechanisms of the system, it is possible, within reason, to redesign a system in order to modify (usually to shorten) the lag. Such reduction, however, may involve engineering complications and costs that are disproportionate to the gain. It is therefore useful to find out the effects of lag upon human use of control devices, leading toward the possibility of specifying the maximum lag that is permissible in terms of desired accuracy.

#### Effects of System Lag

In one sense it is not feasible to discuss the effects of system lag as though such effects are exclusively the consequence of the time lag caused by the mechanism of the system itself. Rather, such effects need to be viewed within the context of the use of a mechanical system by the operator of the system.

#### Anticipation of Input

In some circumstances, the operator can anticipate input changes. This would be possible in a tracking task, for example, where the operator can "see" the course to be followed, such as in driving a vehicle. In other circumstances, where there may be no advance information available to the operator, he may be able to deduce the nature of future signals from past experience; this would be the case, for example, where a person learns the time interval between a warning signal and a subsequent signal to which he is to react or where, in a tracking task, there is a systematic input such as a sine wave.

There is evidence from various studies to the effect that people can compensate fairly well for lag if they are able to anticipate future inputs by either of these methods. Skilled performance in perceptual motor tasks depends to a large extent upon the individual's ability to anticipate and predict system performance; such an ability thus enables an individual to overcome or compensate for his basic "intermittency" and thus to behave as a continuous error-correction device. Without the opportunity to anticipate inputs or outputs, time lags can affect the ability of people to make short-term predictions.

In considering the effects of lag on system output, human reaction time must be considered independently, where it is the exclusive source of lag and in combination with system lag where there is such. While human and system lag can (and do) have adverse effects on system performance in many circumstances (even in such mundane affairs as driving a car), it is evident that it is not invariably a goblin to be avoided at all costs. There are circumstances where its effects can be counteracted and even where it can contribute to the adequacy of system performance.

### Control Backlash and Deadband

There are still other characteristics of control mechanisms that can influence the effectiveness of the use of the controls by human operators such as backlash or deadband. While backlash and deadband can be characteristic of controls of various types and for various uses, they probably are of particular concern in continuous-control tasks.

### Backlash

Performance deteriorates with increasing backlash. Deterioration is related to the gain being used. The higher the servo gain, the greater the deterioration in performance (i.e., the greater the errors) and also the greater the rate of increase in such errors. The implication is that if a high servo gain is used, the backlash (or overspin) needs to be minimized in order to reduce

system errors. Conversely, if it is not practical to minimize backlash, the gain should be as low as possible - also to minimize errors from the operation of the system.

### Deadband

Deadband in a control mechanism is the amount of control movement that results in no movement of the device being controlled. It is almost inevitable that some deadband will exist in a control device. Deadband of any consequence affects control performance, but here again the amount of effect is related to the sensitivity of the control system. It can be observed that performance deteriorates with increase in deadband. Deterioration is less with less sensitive systems than with more sensitive systems. This suggests that deadband can, in part, be compensated for by building in less sensitive control relationships.

The various aspects of control discussed above are predominantly those which have some general implications in control design rather than relating to the quadruped controls only.

## HUMAN FACTORS RELATED TO FORCE FEEDBACK CONTROLS

Many attempts to augment man's ability through mechanical force amplification of his biosystem have failed. This was not because of the lack of a valid system concept, but because of poor understanding of critical human factors. Because of the complex nature of man-machine integration characteristics, great care in design is required. Prerequisite to successful design are: careful study of human factors, design according to human response abilities and authentic laboratory model test and evaluation work.

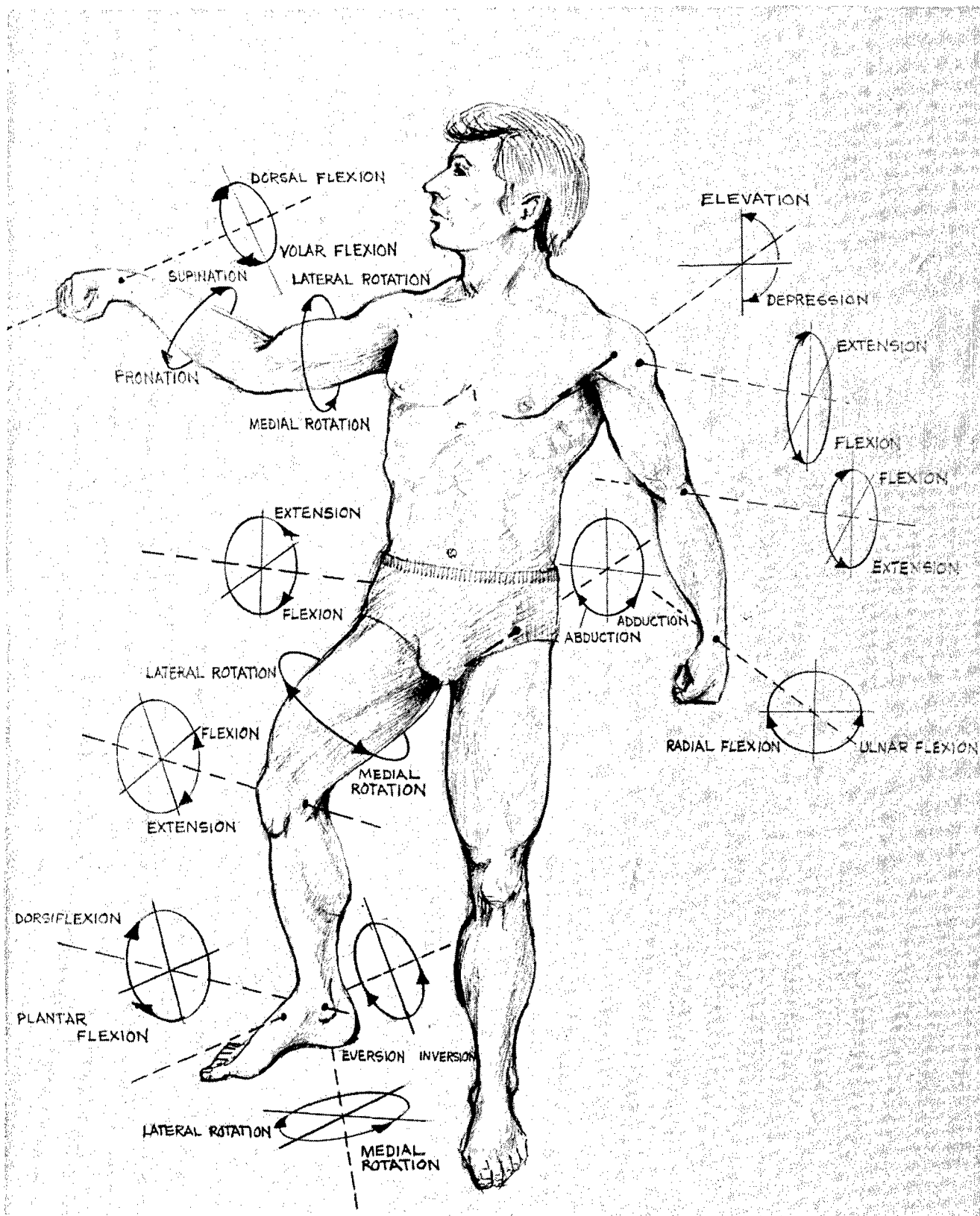
Psychophysical factors and biomechanics of the human system must be understood in order to design controls that can effectively interface man to his machine.

Basic considerations are:

- Biomechanical to mechanical control accord in motions and configurations.
- Definition of each motion, not allowing inseparable redundancy of motions.
- Force control reactions and commands commensurate with human psychophysiological characteristics.
- Spatial correspondence in force vectors between operator and responding machinery.
- Control counterbalance to avoid steady force biases that quickly cause fatigue and limit operator force interpretation thresholds.
- Efficiency of servomechanism controls to provide sharp and accurate resolution of position and force information.

Some of the most significant human factors identified and used for the quadruped test bed program are outlined here as design guidelines for future man-machine design work.

Figure 7 shows the basic human motions most effectively used. Of course, there are many human motions not used. As an example, the human hand has 22 controlled motions. Also, the ankle has thirteen identifiable axes. Exoskeleton controls designed to reflect only basic motions, described in Figure 7, are driven by complex combinations of the human motions. Proper control design allows this to happen without confronting the operator with complications in control.

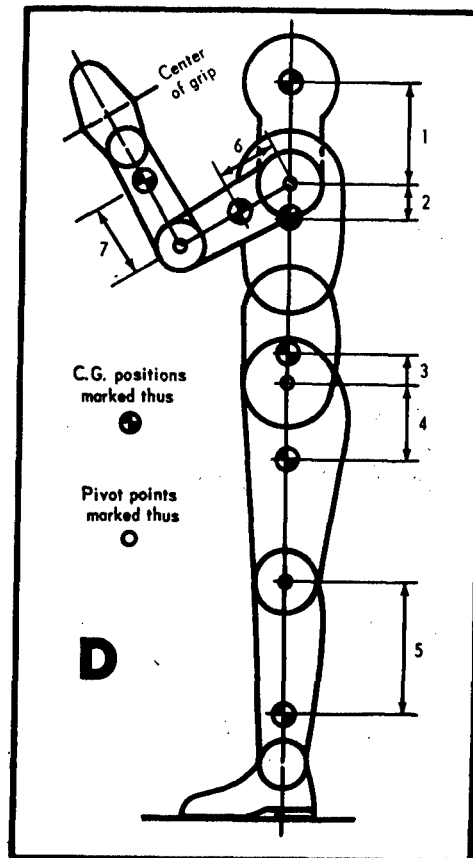
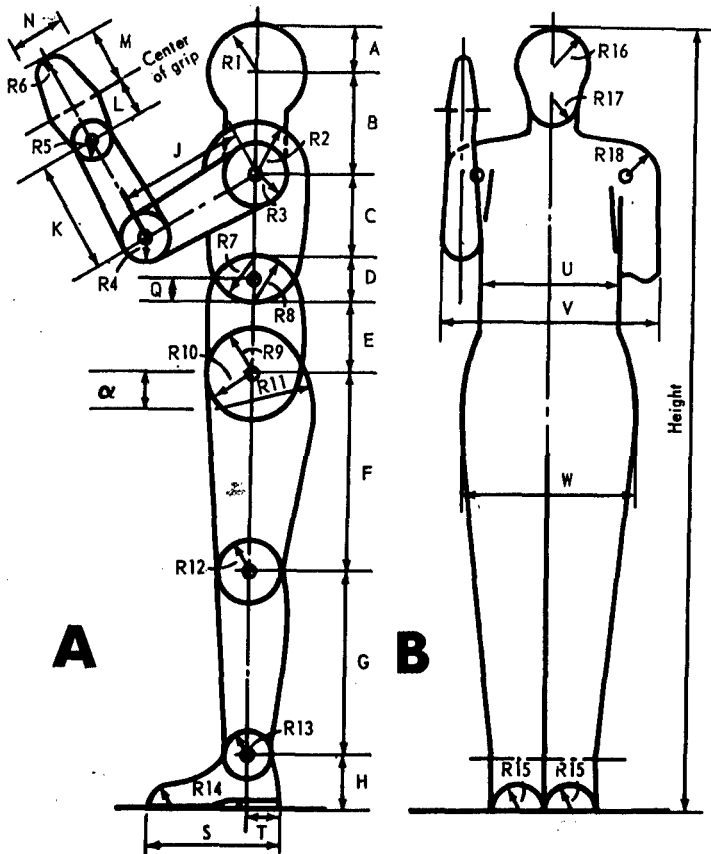
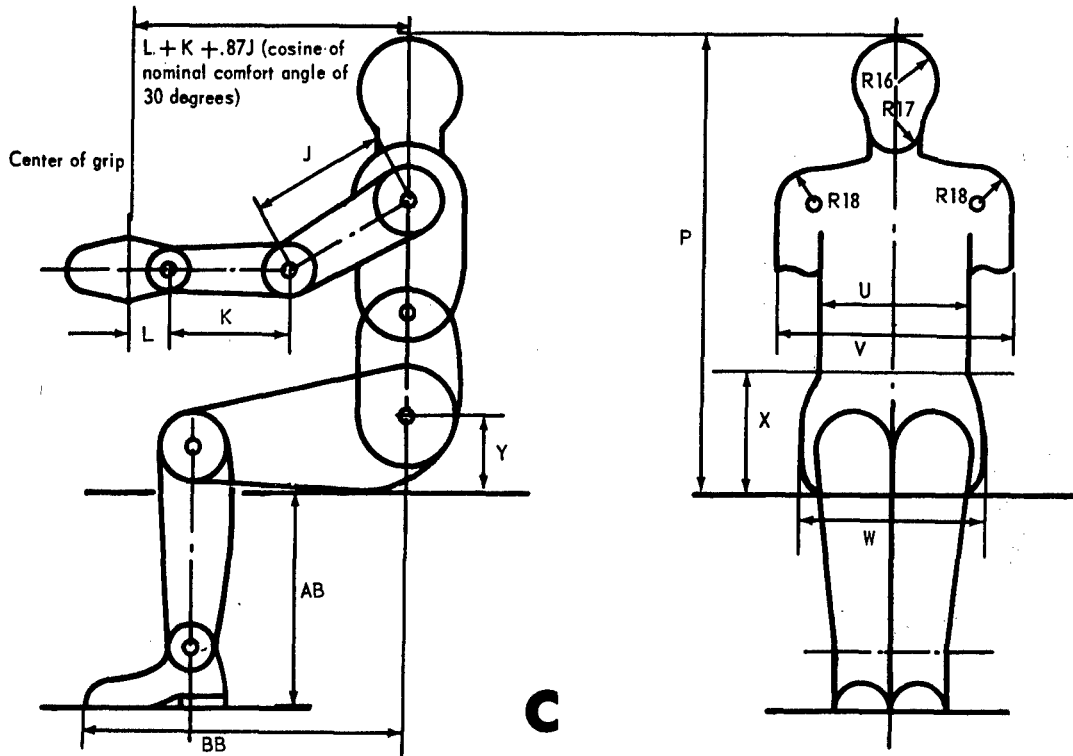


**Figure 7 Human Motions Used for Control**

## GLOSSARY OF TERMS

- Abduction** - The withdrawal of a part from the axis of the body. Of the foot: rotation of the foot outward on its own axis. To move away or to be away from the midline of the body. (For a part to be further away from the midline than normal.)
- Adduction** - Any movement whereby a part is brought toward another or toward the median line of the body. A part of the body is nearer the midline of the body than normal when in adduction.
- Anterior** - Placed forward or to the front of a part; ahead.
- Dorsiflection** - The movement of the foot in an anterior direction about a hypothetical axis passing transversely through the foot.
- Extension** - A straightening out, especially the muscular movement by which a flexed limb is made straight.
- Flexion** - The act of bending, the condition of being bent.
- Lateral** - Toward the outside. (opposite: Medial)
- Medial** - Toward the inside or center.
- Plantar Flexion** - The movement of the foot in a posterior direction about a hypothetical axis passing transversely through the foot.
- Posterior** - Placed behind or to the back of a part; behind.

Figure 8 Body Segments





Redundancy in motions must be avoided. As an example, an exoskeletal arm control system that includes shoulder medial rotation, elbow flexion-extension and forearm supination-pronation could cause confusing redundancy and lack of selective control of one motion with respect to the other. In this example, a straightened elbow causes the shoulder and forearm motion axes to become coaxial. Unless complex attachments are made from exoskeleton to the human arm, definition and control of one motion compared to the other is lost.

This example of redundancy of motion relates to corresponding human leg motions also.\*

Key human physical design factors must be based on fundamental body geometry.

Operator fatigue can be minimized by proportioning working conditions to the basic body geometry of the operator. The average human figure can be analyzed in the form of a geometric model subdivided into twelve pivoted subsections, as detailed in Figure 8A. Table I lists relative dimensions for a range of body heights.

This data can be used in two ways. The simplest, and most direct, is the construction of a card or plastic model to scale, suitably pivoted (e.g. riveted at the pivot points) which can be laid over a drawing and adjusted to various natural attitudes.

Height	5ft. 0in.	5ft. 1in.	5ft. 2in.	5ft. 3in.	5ft. 4in.	5ft. 5in.	5ft. 6in.	5ft. 7in.	5ft. 8in.	5ft. 9in.	5ft. 10in.	5ft. 11in.	6ft. 0in.	6ft. 1in.	6ft. 2in.
1	8.0	8.1	8.2	8.35	8.5	8.65	8.8	8.95	9.1	9.2	9.25	9.3	9.4	9.5	9.6
2	2.25	2.25	2.3	2.35	2.35	2.4	2.45	2.5	2.55	2.6	2.65	2.65	2.7	2.75	2.8
3	2.75	2.8	2.85	2.9	2.95	3.0	3.05	3.1	3.15	3.2	3.25	3.3	3.35	3.4	3.45
4	6.	6.1	6.2	6.3	6.4	6.5	6.6	6.7	6.8	6.9	7.0	7.1	7.2	7.3	7.4
5	10.0	10.2	10.4	10.6	10.8	11.0	11.2	11.4	11.6	11.8	12	12.2	12.4	12.6	12.8
6	4.5	4.55	4.6	4.65	4.7	4.75	4.8	4.85	4.9	4.95	5.0	5.05	5.1	5.15	5.2
7	5.75	5.85	5.95	6.05	6.15	6.25	6.35	6.45	6.55	6.65	6.75	6.85	6.95	7.05	7.15

Alternatively, a figure can be drawn to scale in the required working position and leading dimensions extracted

\* Reference: Biomechanics of Human Motion, by Marian & Issuer, Publisher - W.B. Saunders Company, Philadelphia.

by summing the relevant full size dimensions involved. A selection of examples is given on the following pages and further basic data are extracted in tabular form for direct use. For specific applications, however, it is recommended that the full geometry of the figure be investigated from an accurate scale drawing superimposed on the relevant working conditions.

Basic body dimensions in front view are given in Figure 8B, to which the tabular data of Table 1 again applies. Table 2 and Figure 8C summarize data with the body in a conventional seated attitude.

TABLE 2 SEATED POSITION DATA															
Height	5ft. 0in.	5ft. 1in.	5ft. 2in.	5ft. 3in.	5ft. 4in.	5ft. 5in.	5ft. 6in.	5ft. 7in.	5ft. 8in.	5ft. 9in.	5ft. 10in.	5ft. 11in.	6ft. 0in.	6ft. 1in.	6ft. 2in.
AB	15	15 1/4	15 1/2	15 3/4	16	16 1/4	16 1/2	16 3/4	17	17 1/4	17 1/2	17 3/4	18	18 1/4	18 1/2
BB	22 3/4	23 1/8	23 1/2	23 7/8	24 1/4	24 5/8	25	25 3/8	25 3/4	26 1/8	26 1/2	26 7/8	27 1/4	27 5/8	28

For other dimensions—see table 3

For a more thorough investigation of comfort and fatigue problems, due consideration should be given to the center of gravity positions of the various body components, and to suitable support at these points. Individual center of gravity positions relative to pivot points are detailed in Figure 8D and this data worked out for various heights are given in Table 3. Typical weights are shown in the table below.

NOTE: All dimensions in Tables 1 - 3 are in inches.

Part	Percent of total
Head and neck	6.25
Upper arm	2.5 (x2)
Lower arm and hand	2.25 (x2)
Upper trunk	28.25
Lower trunk	15.5
Upper leg	11.5 (x2)
Lower leg and foot	8.75 (x2)
	100 percent

Percent of Body Segment Weight

TABLE 3 BODY GEOMETRY DATA															
Height	5ft. 0in.	5ft. 1in.	5ft. 2in.	5ft. 3in.	5ft. 4in.	5ft. 5in.	5ft. 6in.	5ft. 7in.	5ft. 8in.	5ft. 9in.	5ft. 10in.	5ft. 11in.	6ft. 0in.	6ft. 1in.	6ft. 2in.
A	3 1/2	3 5/8	3 3/4	3 7/8	4	4	4	4 1/8	4 1/8	4 1/4	4 3/8	4 3/8	4 1/2	4 1/2	4 1/2
B	8 1/4	8 1/4	8 1/4	8 3/8	8 1/2	8 5/8	8 3/4	8 7/8	9	9 1/8	9 1/4	9 3/8	9 1/2	9 5/8	9 3/4
C	5	5 1/8	5 1/8	5 1/4	5 1/4	5 1/4	5 3/8	5 3/8	5 3/8	5 3/8	5 1/2	5 5/8	5 5/8	5 3/4	5 7/8
D	3 1/4	3 1/4	3 3/8	3 3/8	3 1/2	3 5/8	3 3/4	3 7/8	4	4	4	4	4 1/8	4 1/8	4 1/4
E	7 1/4	7 3/8	7 1/2	7 5/8	7 3/4	7 7/8	8	8 1/8	8 1/4	8 3/8	8 1/2	8 5/8	8 3/4	8 7/8	9
F	14 1/2	14 3/4	15	15 1/4	15 1/2	15 3/4	16	16 1/4	16 1/2	16 3/4	17	17 1/4	17 1/2	17 3/4	18
G	14	14 1/4	14 1/2	14 3/4	15	15 1/4	15 1/2	15 3/4	16	16 1/4	16 1/2	16 3/4	17	17 1/4	17 1/2
H	4 1/4	4 3/8	4 1/2	4 1/2	4 1/2	4 5/8	4 5/8	4 5/8	4 3/4	4 7/8	4 7/8	5	5	5 1/8	5 1/8
J	9 1/2	9 3/4	10	10 1/8	10 1/4	10 1/2	10 3/4	10 7/8	11	11 1/8	11 1/4	11 1/2	11 3/4	11 7/8	12
K	8 1/2	8 3/4	9	9 1/8	9 1/4	9 3/8	9 1/2	9 5/8	9 3/4	9 7/8	10	10 1/8	10 1/4	10 3/8	10 1/2
L	3	3.05	3.1	3.15	3.2	3 1/4	3.3	3.35	3.4	3.45	3 1/2	3.55	3.6	3.65	3.7
M	3 1/4	3 3/8	3 3/8	3 1/2	3 1/2	3 1/2	3 1/2	3 1/2	3 5/8	3 5/8	3 3/4	3 3/4	3 7/8	3 7/8	4
N	4.85	4.05	4.1	4.15	4.2	4 1/4	4.3	4.35	4.4	4.45	4 1/2	4.55	4.6	4.65	4.7
P	32	32 1/2	33	33 1/2	34	34 1/2	35	35 1/2	36	36 1/2	37	37 1/2	38	38 1/2	39
Q	1.65	1.7	1.7	1.75	1.75	1.75	1.8	1.8	1.85	1.85	1.9	1.9	1.95	1.95	2.0
S	10	10 1/4	10 1/2	10 3/4	11	11 1/4	11 1/2	11 3/4	12	12 1/4	12 1/2	12 3/4	13	13 1/4	13 1/2
T	2.5	2.55	2.6	2.65	2.7	2.75	2.8	2.85	2.9	2.95	3.0	3.05	3.1	3.15	3.2
U	11 1/2	11 3/4	12	12 1/4	12 1/2	12 5/8	12 3/4	12 7/8	13	13 1/4	13 1/2	13 3/4	14	14 1/4	14 1/2
V	16 3/4	17	17 1/4	17 1/2	17 3/4	18	18 3/8	18 3/4	19	19 1/4	19 1/2	19 3/4	20	20 1/4	20 1/2
W	13 1/4	13 1/2	13 3/4	13 7/8	14	14 1/4	14 1/2	14 3/4	15	15 1/4	15 1/2	15 3/4	16	16 1/4	16 1/2
X	8.2	8.35	8.50	8.65	8.8	8.95	9.1	9.25	9.35	9.45	9.55	9.65	9.75	9.90	10.05
α	2.8	2.85	2.9	2.95	3.0	3.05	3.1	3.15	3.2	3.25	3.3	3.35	3.4	3.45	3.5
R1	3 1/2	3 5/8	3 3/4	3 7/8	4	4	4	4 1/8	4 1/8	4 1/4	4 3/8	4 3/8	4 1/2	4 1/2	4 1/2
R2	4.15	4.2	4.25	4.3	4.35	4.4	4.45	4.5	4.55	4.6	4.65	4.7	4.75	4.8	4.85
R3	2.35	2.35	2.4	2.45	2.5	2.55	2.6	2.65	2.7	2.7	2.75	2.75	2.8	2.8	2.85
R4	2.0	2.0	2.05	2.05	2.1	2.1	2.15	2.15	2.2	2.2	2.25	2.25	2.3	2.3	2.35
R5	1.5	1.5	1.55	1.55	1.6	1.6	1.65	1.65	1.7	1.7	1.75	1.75	1.8	1.8	1.85
R6	1.65	1.7	1.7	1.75	1.75	1.8	1.8	1.85	1.85	1.9	1.9	1.95	1.95	2.0	2.0
R7	3 1/4	3 1/4	3 3/8	3 3/8	3 1/2	3 5/8	3 3/4	3 7/8	4	4	4	4	4 1/8	4 1/8	4 1/4
R8	3 1/4	3 1/4	3 3/8	3 3/8	3 1/2	3 5/8	3 3/4	3 7/8	4	4	4	4	4 1/8	4 1/8	4 1/4
R9	3.55	3.6	3.65	3.7	3.75	3.8	3.85	3.9	3.95	4.0	4.05	4.1	4.15	4.2	4.25
R10	3.55	3.6	3.65	3.7	3.75	3.8	3.85	3.9	3.95	4.0	4.05	4.1	4.15	4.2	4.25
R11	7.75	7.85	7.95	8.05	8.15	8.25	8.35	8.45	8.55	8.65	8.75	8.85	8.95	9.05	9.15
R12	2.5	2.55	2.6	2.65	2.7	2.75	2.8	2.85	2.9	2.95	3.0	3.05	3.1	3.15	3.2
R13	2.15	2.2	2.25	2.3	2.35	2.4	2.4	2.45	2.45	2.5	2.5	2.5	2.55	2.55	2.6
R14	2.15	2.2	2.25	2.3	2.35	2.4	2.4	2.45	2.45	2.5	2.5	2.5	2.55	2.55	2.6
R15	2.15	2.2	2.25	2.3	2.35	2.4	2.4	2.45	2.45	2.5	2.5	2.5	2.55	2.55	2.6
R16	3.3	3.35	3.4	3.45	3.5	3.55	3.6	3.65	3.7	3.75	3.8	3.85	3.9	3.95	4.0
R17	2.15	2.2	2.25	2.3	2.35	2.4	2.4	2.45	2.45	2.5	2.5	2.5	2.55	2.55	2.6
R18	2.5	2.55	2.6	2.65	2.7	2.75	2.8	2.85	2.9	2.95	3.0	3.05	3.1	3.15	3.2

Note: Apparent inconsistency in dimensions shows relative accuracy to which dimensions are normally measured.

## DESCRIPTION OF HUMAN LOCOMOTION

A bipedal "pedipulator" has been under development for eons in the form of the human body. Knowledge of the locomotion of this exquisite mechanism is certainly invaluable in the development of man-machine force feedback mechanisms. There is an enormous amount of information on the morphology of the human which we cannot begin to review here. This discussion will therefore be restricted to the elementary kinematics and dynamics of human locomotion.

### Mechanism Used in Standing Upright. Balancing

A human being is in gravitational equilibrium as long as his center of gravity is vertically above the centroid of the area of contact of his feet with the floor. In upright standing, the vertical through the center of gravity of the body falls about  $1\frac{3}{4}$  inches in front of the center of the ankle joints. The calf muscles thus have to exert a force to counteract the moment due to the weight of the body at this  $1\frac{3}{4}$ -inch radius.

Other muscles must exert forces at the other joints such as the knee, hip and spine, in order that this articulated chain of links remain erect since these joints do not lie on a vertical line through the center of support.

In maintaining his center of gravity above the center of the area of support of his feet on the floor, a human uses several mechanisms. To maintain side to side balance, especially on one foot, he uses opposing muscles on the sides of the ankle joint to move the mobile subtalar joint. The action of these muscles in controlling body balance, however, does not operate through their ability to move the center of gravity of the body. These muscles are too small to rotate the entire inertia of the body about the ankle. Instead, they move the joint under the center of gravity as a person does when he is balancing an inverted golf club vertically on his hand. He controls the club's balance by short quick movements of the lower end against the inertia of the upper end of the club. In this way the

equilibrium of the club is maintained by movements beneath the club's weight center. The ankle muscles act similarly. If the body's center of gravity shifts out of balance laterally, these muscles move the center of the ankle joint quickly beneath or slightly beyond the body center, and thereby induce it to return to the null position. These ankle movements are small but can easily be seen when one stands on one foot. This suggests a similar balance mechanism which might be applied to the ankles of leg-controlled mechanisms.

The maintenance of fore and aft balance requires the larger muscles of the calf, etc., to move the center of gravity over the center of support. If the center of gravity moves beyond the limits of the area of support of the feet, no action of the ankle muscles can correct the balance. When this happens, the human moves his foot (or feet) under or beyond the center of gravity by sliding, stepping, or hopping. In many cases several balancing adjustments are required because a person often makes an overcorrection or undercorrection. For large unbalances, a human will flail his arms and the upper part of his body against the direction of a fall. The resulting reaction force may momentarily give him the opportunity to regain his footing. This is a last ditch effort, however, because when his arms can no longer be accelerated against the direction of the fall, he will proceed to fall until he reaches his next point of support at a lower energy state. The state of balance and equilibrium in the human is achieved by continuous action of the various neural and muscular servo loops in the body. Even when the human is standing still there is some body sway or tremor about his equilibrium position. The human will necessarily oscillate between the threshold limits of tilt that he can detect.

Basic leg motions, and average amplitudes are as follows:

Hip rotation about y axis	113° total
Hip rotation about z axis	34° inward
Hip rotation about z axis	39° outward
Hip rotation about x axis	31° inward (adduction)
Hip rotation about x axis	53° outward (abduction)
Knee rotation about y axis	160° total

Ankle rotation about y axis	35° flexion
Ankle rotation about y axis	38° extension
Ankle rotation about x axis	24° inward
Ankle rotation about x axis	23° outward

There are other small rotations such as rotation of the knee about the x and z axes and the ankle about the z axis. (See Figure 9.)

These motion limits would be required for a machine having the agility of a man. These motions could provide squatting, sharp turns, and stepping over objects proportional to the machine's size.

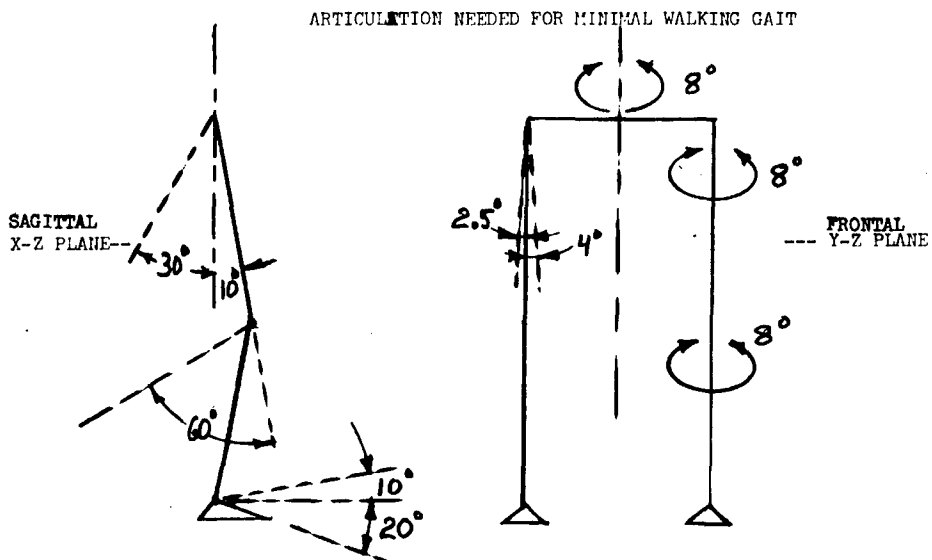
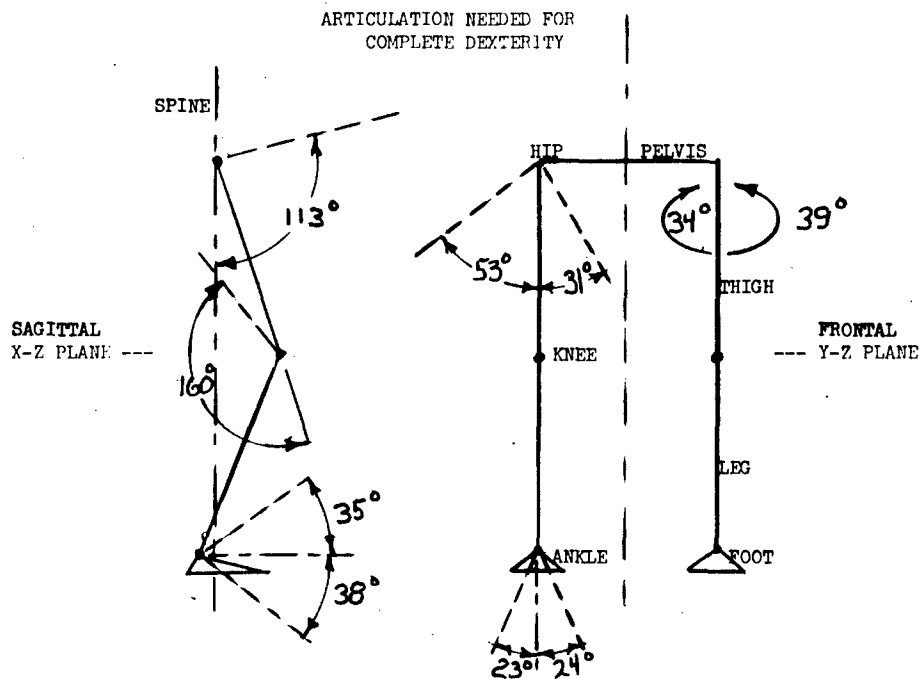
For walking on level terrain, the angles of interest are those used by the human in a straight level walk. The angles of excursion of the human joints in normal level walking are:

Hip rotation about y axis	-30° to +10°
Hip rotation about x axis	4° inward (adduction)
Hip rotation about x axis	2.5° outward (abduction)
Knee rotation about y axis	-60°
(angle between thigh and leg)	
Ankle rotation about y axis	10° flexion
	20° extension
Rotation of pelvis about z axis	8° total
Rotation of thigh bone about its axis with respect to the pelvis	8° total
Rotation of the tibia about its axis with respect to the femur	8° total

These last three axial rotations are not in phase so that the absolute rotation of the leg bone is 19° and the absolute excursion of the thigh bone is 15° about its axis. Thus, neglecting the small rotation of the ankle about the axis of the leg, the foot rotates about 19° relative to the pelvis in normal straight walking.

In the frontal plane or y-z plane, there are the following absolute rotations of the skeletal members. (See Figure 10.)

**Figure 9 Leg Dexterity**



**Figure 10 Dexterity Needed for Walking Gait**

Pelvis rotation about x axis	+4° and -5°
Rotation of the femur with respect to the pelvis	+7° to -6°
Rotation of the tibia with respect to the femur	+4° to -4°

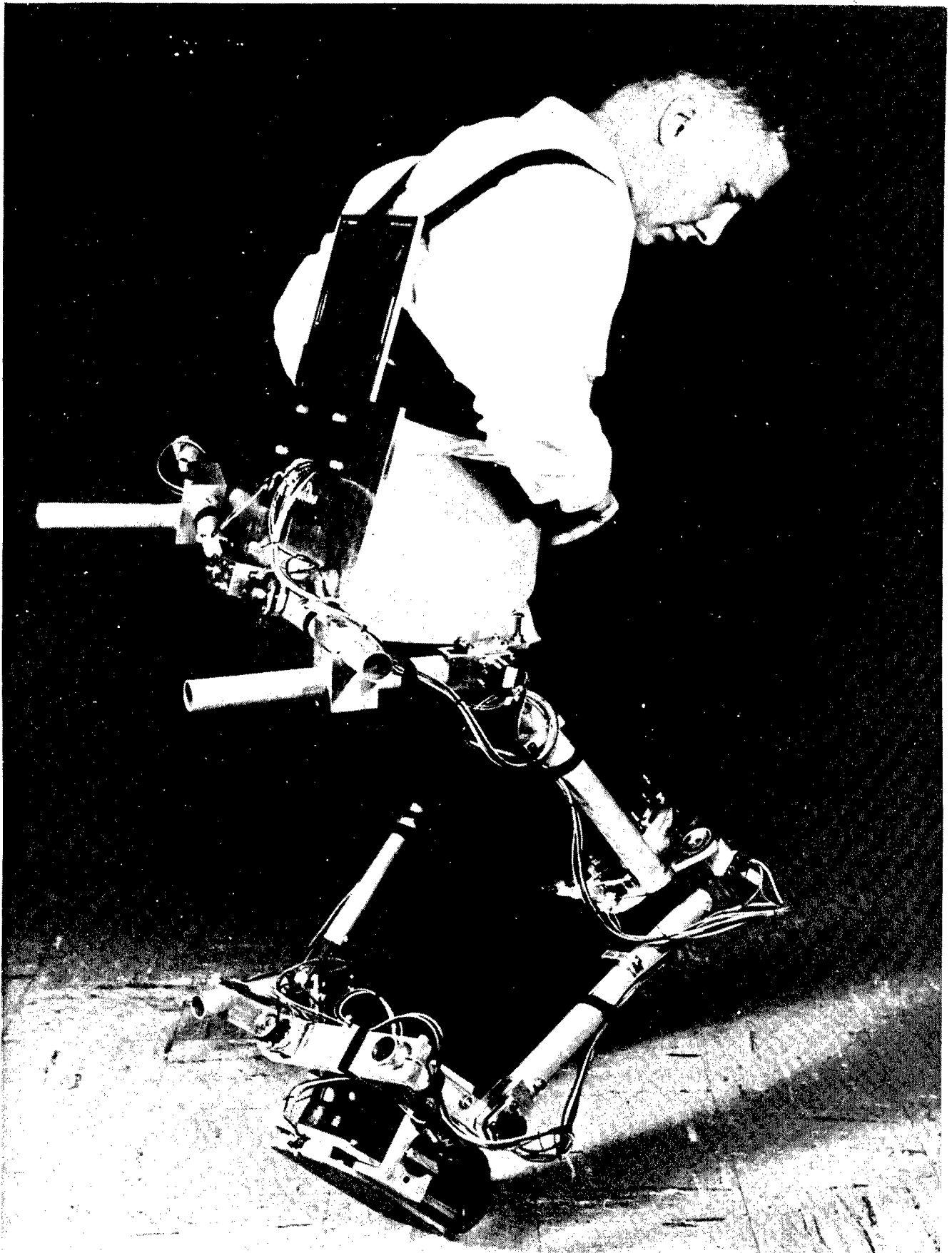
The number of degrees of freedom and the ranges of the joints which should be designed will depend upon the mission to be accomplished. For a useful degree of agility and balancing capability, a minimum of six degrees of freedom in each leg appears to be required for a walking machine. Making a forward step requires three degrees of freedom - one axis of rotation at the hip, one rotation at the ankle and a rotation or extension at the knee. An additional degree of freedom would be required at the hip and/or ankle joints to allow for deviation in foot orientation from a line parallel to the direction of body movement. Adjusting the plane of the foot to the terrain requires an additional axis of rotation. For side to side balance, abduction at the hip is required. These five joints are sufficient to accomplish forward motion. In order to turn to the right or left, rotation of the foot about the axis of the leg relative to the pelvis, or body of the vehicle, is required. This rotation could be in the ankle, the hip, or at any point along the leg. This adds up to the minimum of six joints per leg.

In walking, the two extremities alternate in their periods of support and swing. The supporting phase begins with the moment the heel is set on the ground, and it ends with the moment the big toe leaves the ground. The swinging phase begins at the end of the supporting phase or "toe up" and ends with heel down. In walking, the durations of these two phases are not equal. The supporting phase lasts longer than the swinging phase. There is thus a period of double support when both feet are on the ground simultaneously. As the speed of walking increases, the durations of these two phases approach equality. In running, however, the duration of the swing phase is greater than that of the support phase, so there is a period in running where the two swing periods overlap and both feet are off the ground.

The three figures (11, 12 and 13) show an experimental exoskeleton leg system used to measure motion amplitudes,



Figure 11 Leg Exoskeletal Kinematic Measurements



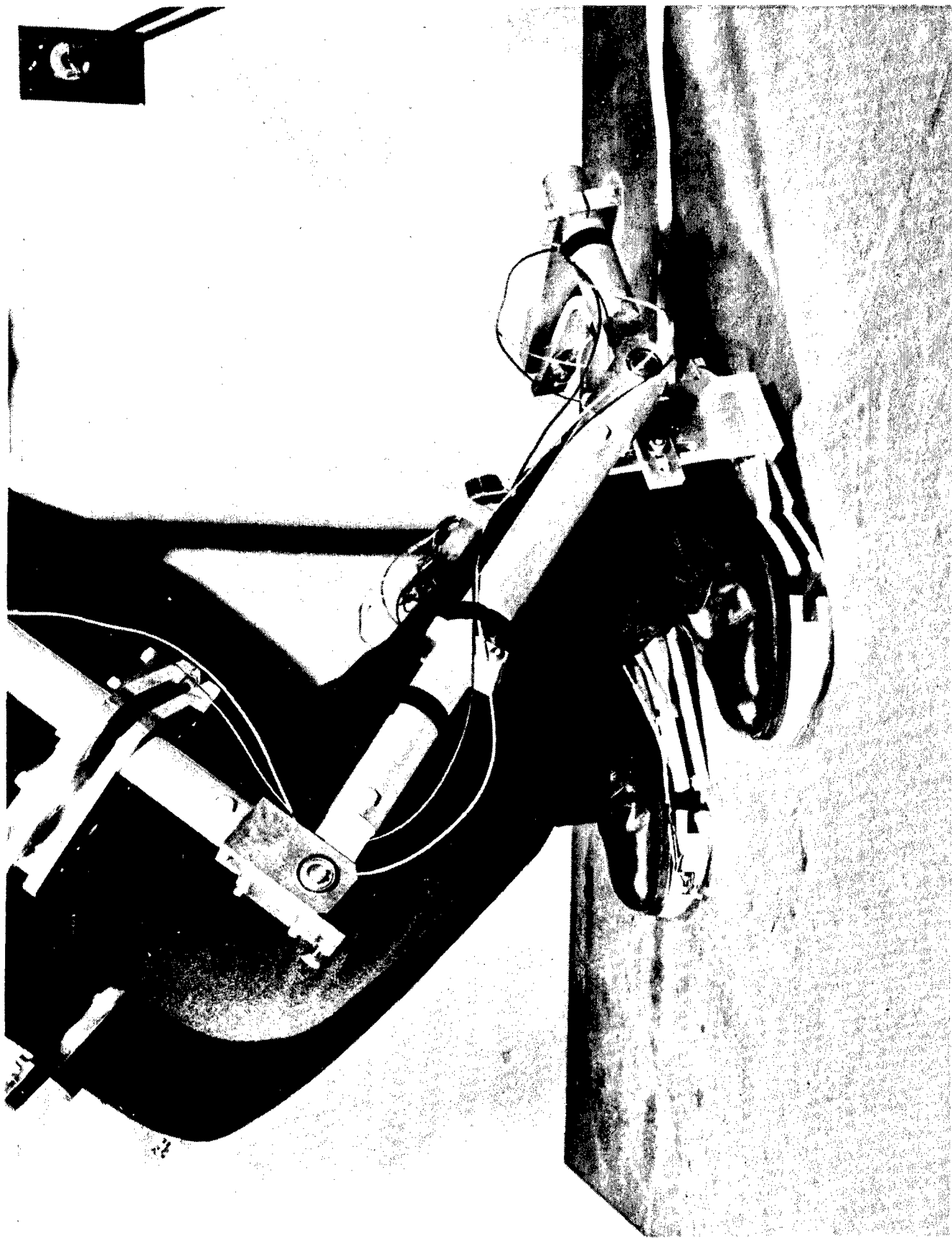


Figure 12 Leg Exoskeletal Kinematic Measurements



Figure 13 Leg Exoskeletal Kinematic Measurements

suitability of kinematics for unrestrained walking and effects of limited leg motions.

### Dynamics of the Human Locomotor Mechanism

To provide some insight into the nature of bipedal locomotion, a brief description of the gross dynamics of the human's locomotor mechanism is presented here.

Walking is initiated by the relaxing of the calf muscles which are supporting the center of gravity of the body over the center of the feet. Upon relaxation of these muscles, the body begins to fall forward. During this fall, one leg is lifted and advanced for the first step.

In normal level walking the center of gravity of the body, which is located just above the line of the hip joints, describes a smooth sinusoidal curve in the plane of progression, with a frequency equal to the step frequency. This occurs because the body rises as it vaults over each leg alternately. The center of gravity also goes through a sinusoidal curve in the horizontal plane, with half the step frequency, as the weight of the body shifts from one leg to the other.

The functions of the various articulations in the human locomotor mechanism are of interest in the design of a walking or leg-controlled mechanism. First, consider a bipedal system in which the two legs are rigid levers without feet, pivoted at the hip joints. The motion of the pelvis in a walk of this simplified model would consist of a series of intersecting arcs in the plane of progression, with radii equal to the leg length. At the intersection of the arcs, or lowest points in the stride, there is a sharp discontinuity where the weight is transferred from one leg to the other. At this point there would be large acceleration forces built up along with the loss of the energy associated with the fall from the summit of the arc of motion. All of the additional articulations in the human locomotor mechanism, other than the hip articulation, serve to reduce the amplitude of the above mentioned arcs and to smooth out the discontinuities. The rotation

of the pelvis about the vertical axis, tilt of the pelvis toward the unsupported leg, flexion of the knee, and flexion of the ankle, all tend to increase the effective radius of the arc through which the center of gravity passes, decrease its amplitude and smooth out the transition from one leg to the other. Each of these mechanisms reduces the forces on the system and the energy required for walking. The absence of any one of these articulations increases the power required and the force levels, although, it may not prevent the person from performing a satisfactory walk. The human can compensate for the loss of mobility of one joint through exaggerated motions in the other joints, to maintain the same normal pathway of the center of gravity. For example, high heels worn by women reduce mobility of the foot and ankle joints, thus, decreasing their contribution to a normal gait. To compensate for this the initial knee flexion is increased and the pelvic tilt and rotation are exaggerated, producing the characteristic gait which is familiar to all.

To some extent, these human compensatory articulations were effective through exaggerations of action by the basic three motions of the quadruped leg (two in the hip, and one on the knee). See Figure 14 showing quadruped motions. The exoskeletal harness shown in Figures 11, 12 and 13 was used to measure amplitudes and their time derivations.

While walking, the human swings his arms  $180^{\circ}$  out of phase with his legs to counteract the angular momentum of the lower extremities and minimize the angular rotation of the upper part of the body. The swinging of the arms is actually due to muscular action and not merely the free motion of a pendulum.

During a walking stride, the foot transmits shear forces to the ground. The fore and aft shear force varies from 30 pounds forward to 20 pounds in the reverse direction. The lateral shear has an amplitude of about 7 pounds. There is also a torque transmitted to the ground which has a magnitude of about 60 inch-pounds. All of these forces occur, in addition to the vertical force, when the subject is walking on level ground at a constant rate. It is



evident that high friction is necessary for the execution of a walk. Loose ground and slippery surfaces do not readily support shear forces, and it is, therefore, more difficult to walk on them. On loose and slippery surfaces the length of stride and speed must be reduced to reduce the transmitted shear forces.

### Energy Consumption in Human Walking

Of all of the types of animal locomotion including sliding, crawling, leaping, running and walking, the walk of the human is the most efficient in terms of power expended per pounds of weight per feet per second of velocity. Manmade vehicles using wheels or tracks become more efficient than animal locomotion only in firm, smooth surfaces.

It is interesting to compare the specific power of various vehicles. The specific power is equal to the power required for propulsion,  $P$ , divided by the product of the gross vehicle weight,  $W$ , and the velocity,  $V$ . The approximate specific power of a few vehicles are tabulated below.

<u>Vehicle</u>	<u>Specific Power <math>\frac{P}{WV}</math></u>
Helicopter	0.2
Hovercraft	0.2
Truck on smooth firm surface	.07
Cross-country vehicle	0.5
Human walking at 2.9 miles per hour	0.18
Human running at 5.7 mph	0.42

The energy consumed by the human in straight and level walking is divided approximately equally between the energy expended in raising and lowering the center of gravity and that used in moving the limbs.

It is not yet known whether a mechanical walking machine can be built with a specific power equal to or less

than the human or the helicopter. There is no fundamental reason why it cannot be done, however. The human walking machine is rather inefficient since a muscle consumes energy when it is doing no work and even when work is being done on it. The kinetic and potential energy put into the legs by the muscles is lost with each step, and the potential energy associated with the rise and fall of the center of gravity of the human body is lost with each step. There is no spring or other energy storage system in the human mechanism which might store and transfer this energy from one step to the next. Human locomotion is most efficient when one walks with a natural "unforced" gait. When one runs, the efficiency goes down.

For the quadruped test bed, servo mechanism design was specified with primary regard for development costs rather than efficiency. The type servo used caused power consumption proportional to leg motions, regardless of forces generated. Therefore, a free-swinging leg actually takes more power than the slower but high force leg support and drive action. Therefore, the existing system power consumption is not an indication of potential power efficiency.

Variable displacement hydraulic pumps, one for each servo, are needed for efficient power use for all machines of this type control and multimotion systems.

#### HUMAN ORIENTATION AND EQUILIBRIUM

The human being uses primarily three senses to determine his orientation and equilibrium: his eyes, the labyrinth of his inner ear, and his kinesthesia or muscle sense. The kinesthetic sense is the one by which a person determines the position and extent of forces in the various parts of his body, making possible the coordination of physical activity such as walking. The kinesthetic signals originate in nerve endings located on the muscles, tendons and joints. Kinesthesia is also necessary for maintaining equilibrium and an upright posture. It tells a person the angular position of the neck, back, waist, and leg joints so that buckling of this articulated column can be controlled.

The labyrinth of the inner ear provides sensors to detect linear acceleration and the direction of the gravity vector.



On each side of the head there are three semicircular canals, approximately in the three orthogonal planes of space. These canals are filled with a watery liquid. If any angular acceleration occurs in the plane of a canal, the fluid tends to lag behind bending certain hair tufts. Nerve endings in the hairs provide the signals. Other receptors in the inner ear called the utricle and the saccule respond to the combined gravity and linear acceleration vectors. The response is initiated by the action of tiny calcium carbonate particles in a gelatinous mass into which hairs project. Nerve endings in the hairs are excited by motion of the particles.

Aside from detecting obstacles and irregularities in the path of motion, the eyes enable a person to judge the vertical more accurately as long as the visual is in alignment with the local gravity vector. The eyes also help to reduce body sway when standing still.

To estimate the possible performance of a man-operated Pedipulator, the thresholds for sensitivity to linear and angular acceleration and tilt off the vertical should be known.

The threshold for linear horizontal acceleration is 12 to 20 cm/sec<sup>2</sup>.

The threshold for linear vertical acceleration is 4 to 12 cm/sec<sup>2</sup>.

The threshold for angular acceleration drops from 4.5 degrees/sec<sup>2</sup> at time duration of the stimulus of 2 seconds to 1.5 degrees/sec<sup>2</sup> for 16 seconds and longer.

The average threshold for tilt from the vertical for a group of normal subjects in the absence of a visual framework was found to be 1.7° in an experiment described in Reference 38. With visual cues, the threshold should be much smaller.

#### OTHER TYPES OF WALKING MACHINES

Several types of walking mechanisms have been conceived in the past. All of these mechanisms use legs made of

Figure 15 Balance Experiment Action



Figure 16 Balance Experiment Controls



mechanical links. To maintain stability they use a large number of legs, anywhere from 6 to 16, so that the center of gravity is always supported inside a minimum of three supports. The large number of legs creates considerable complexity, but it provides the vehicle with good support. These walking machines can operate well on smooth plane surfaces just as the many children's walking toys do. They are not suitable for locomotion over irregular terrain, which is the primary mission for an off-road vehicle. A walking vehicle which could accomplish this would have to have a control system which would sense the contour and consistency of the terrain and determine and control the position and speed of each foot continuously. Such a control system may be possible, but it does not appear practical.

The pedipulator overcomes this hurdle by using the existing sensing and control system of the human locomotor mechanism. Figures 15 and 16 show the balance experiment device and its controls. This force feedback controlled device was easily balanced by a great number of subjects. It proved that the force feedback and spatial correspondence of position allows the human operator to balance large machines.

#### ANIMAL LOCOMOTION

Most animals are quadrupeds. Many birds are bipedal, including the ostrich which depends solely on walking for locomotion. A quadruped is basically two bipeds in series. The action of each pair of legs in a quadruped is the same as that of a biped. A quadruped requires less effort to maintain balance because four supports are inherently more stable than two. There is, however, the additional problem of synchronizing the rear legs with the front ones.

It would be more natural and simpler for the human operator to control a two-legged pedipulator than a four-legged one.

A two-legged experimental pedipulator would yield a lot more information on the problems of balancing and agility and would be less complex than a four-legged one.

The efficiency of human walking is exceeded by wheeled vehicles only on hard smooth surfaces. The most inherently, efficient form of locomotion is the rolling of a rigid wheel on a rigid track.

M. G. Bekker concludes in his book "Theory of Land Locomotion": "It thus appears justifiable to conclude that in off-the-road locomotion, the walking, and to a large extent, the running animals are unsurpassed by man-made vehicles. They are not only faster, more economical, reliable and versatile, but also most adaptable to changing environment."

Fundamentally, he is correct. To achieve this level of proficiency with walking machines would require mechanisms controls and sensors equal to unapproachable human biological systems. The best we can hope for is improved designs and simple systems of limited but useful capabilities.

## EXOSKELETAL OPERATOR CONTROL KINEMATICS DESIGN CONSIDERATIONS

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Several examples of exoskeletal control mechanisms are illustrated in this report. Because of the stringent design requirements dictated by compatibility of master control and the human appendage, exoskeletal control harness designs always involve extensive compromises. Therefore, for each new system concept it is important to design the controllers to take full advantage of all design opportunities commensurate with the given set of operating parameters. The main problem is not a lack of willingness to compromise in design for minimum acceptable performance, but a rather mere achievement of acceptable performance.

Figure 7 is an illustration of the human anatomy and definitions of the significant biomechanical motions used for control in this kind of equipment. There are seven motions shown for each appendage and the use of all seven would be ideal. This, however, would result in undue complications in control design; and, while utilization of all would offer added dexterity, this benefit would be more than offset by the added complexity of the system. The following are a set of rules suggested as guidelines for the design of this type of multimotion controller:

1. Try to achieve satisfactory integrity of man and controller with a minimum of attachments to the operator.
2. Provide adequate attachments between controller and operator so as to provide good and meaningful force and position couplings for transmission of force feedback and position signals between master controller and operator.
3. Where a multiplicity of motions are employed, it is important to avoid operating conditions where mechanical locking occurs (i.e., gimbal locks where the axes of two motions become coaxial or parallel.).
4. Retain spatial correspondence between master and slave with respect to position and force information.

Some deviations are acceptable and, as a general rule,  $30^{\circ}$  is the upper limit. Ninety degrees causes an impossible situation for this kind of control.

5. Retain a linear and constant relationship in master-to-slave motion and force ratios. It is also important that the portions of force reflected to different parts of the human appendage by the various mechanical contacts be proportional to the normal force levels of these human appendage segments.

6. The master controller must be counterbalanced so that the operator is not subjected to continuous lifting forces caused by the dead weight of the controller. This is usually done with counterweights, springs, or servo control or special designs of the kinematics so that the counterweighting force is negligible.

7. Keep the amplitude of motion required by the operator at a maximum value within a comfortable operating range. This provides maximum opportunity to provide accurate positioning capability of the slave output members.

8. Keep the reflected forces to the operator at a maximum value for the purpose of providing crisp definitions of forces generated or encountered. The upper limit of these force values is determined by operator safety and work endurance considerations.

9. Carefully design the kinematics of the master controller to keep friction and viscous drag to a minimum. These factors can cause serious degradation to the performance of the system.

10. To enhance overall control design, consider the possibilities of deviations in correspondence within allowable limits. It is possible to use unsimilar master-slave relationships with mathematical conversion techniques implemented by computer control. This means that within practical limits the kinematics of the master does not necessarily need to be patterned after the kinematics of the slave station.

11. With the motions and forces of the slave system specified and the rules set forth here in regard to maximum motion and forces reflected to the operator, the gains of force and motion between master and slave are defined. The higher the gain force used the more critical the accuracy of force reflection becomes, and likewise the same holds true for high gain in motion.

The Argonne National Laboratory master-slave manipulator design (by Raymond Goertz) is a very ingenious one where the kinematics do not conform to the biomechanics of the human arm. The reason for this deviation was that large amplitudes of motions were needed and a normal one-to-one patterning of controller-to-operator motions would have caused serious problems in mechanical or gimbal locking. The long vertical arm hung from high above provides large amplitudes without corresponding large angular motions at the pivot joints. In this case the master and slave kinematics are identical. However, it is possible to build the slave system differently and provide conversion computer control techniques that would let the operator and slave end effectors retain spatial correspondence.

The picture of "Handyman" (see Figure 1) shows another example of deviation in kinematics. The upper arm twist and elbow motions are reversed in sequence between master and slave. Because of the small amplitude of motion required for this manipulator, the deviations in spatial correspondence are not severe enough to be confusing to the operator. The reason for this change in sequence of motions is to enhance the design of the slave system and at the same time overcome a difficult design problem in having the master station conform and be in juxtaposition with the operator. It is interesting to note that the slave forearm could rotate a total of 300 and this corresponded to 120° rotation of the master. This means that each end of master and slave strokes, the slave was out of synchronism by 90°. This error was very confusing to the operator in deciding which was the finger and which was the thumb. (Finger and thumb were operated independently.)



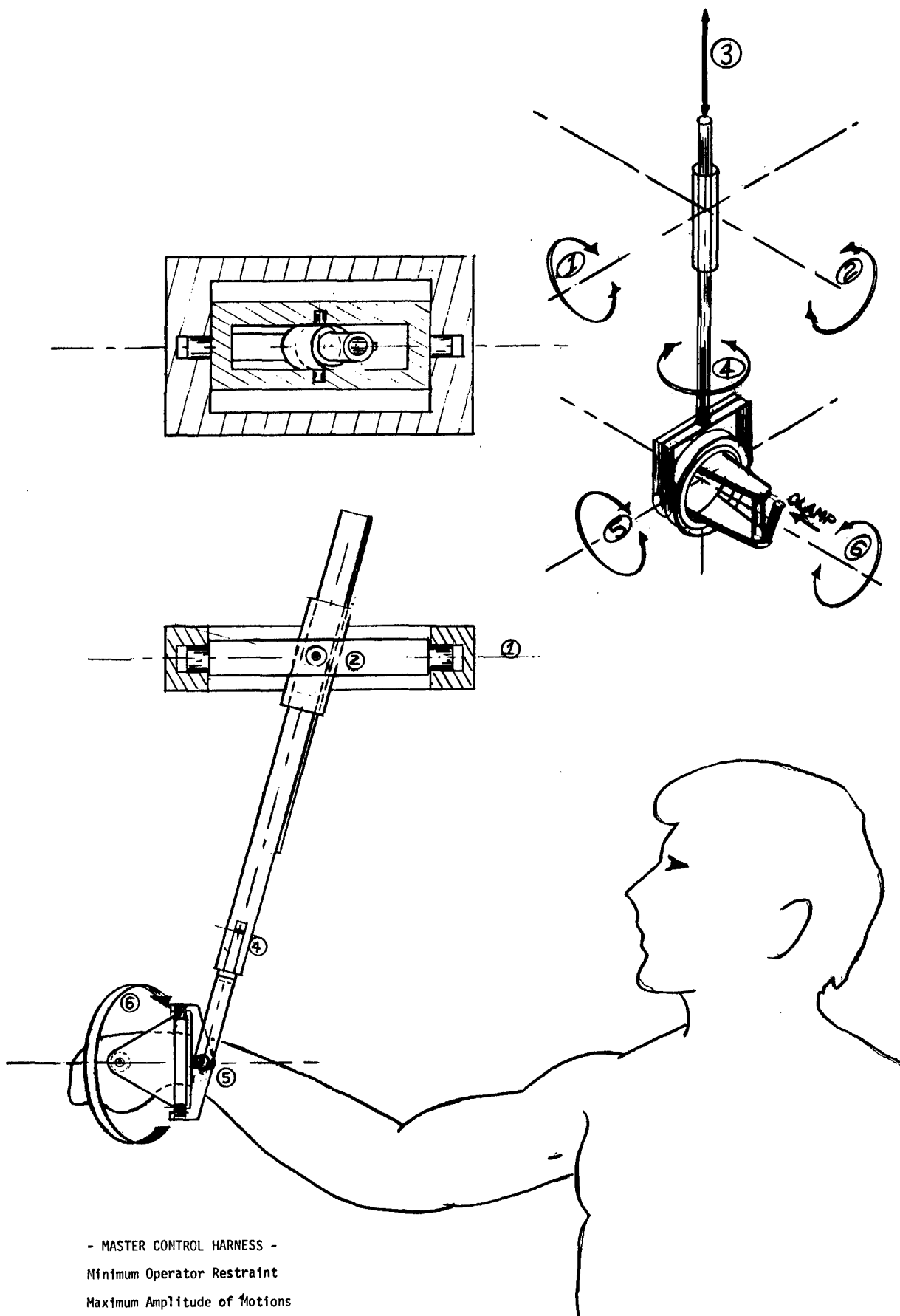
In general, the design of a master controller is developed after many laboratory model mock-up tests. The complexity of the kinematics warrants such careful experimental test procedures.

Figure 17 shows an arm master control harness concept that incorporates six motions. The long vertical arm limits the primary gimbal motions numbers 1 and 2 to an amplitude that prevents undesirable parallel positions to two axes. The second significant point in regard to this design is the limited restraint required for harness-to-operator connections. Also, with this arrangement, there is a minimum of control harness counterweighting problems. The operator has the ability to move his hand control in and out and left and right a large distance without harness kinematic limitations or forces unrelated to the control system caused by incongruities of the interface attachments between operator and harness.

An example of redundancy of two motions that can occur by manipulation maneuvers may be shown with this illustration. The axes of motions 1 and 4 could become coaxial if motion number 2 were allowed to swing far enough. If this were allowed to happen, the operator would find it difficult to control one motion as compared to the other. The two motions would then become an indeterminant differential linkage system. In the case where the harness must be anthropomorphic and located in juxtaposition with the operator's appendage, this fault can be avoided by additional attachments to the operator. Of course, these added attachments represent added complexity and limitations of the man-machine control functions.

A leg harness control system with six degrees of freedom is defined in Figure 18. This concept shows a harness that is more anthropomorphous than the arm control harness described above. The hip motions, 1 and 2, could be created in the same manner as in the arm harness control.

It is interesting to note that two body attachments are required for this system. One is the clamp attachment



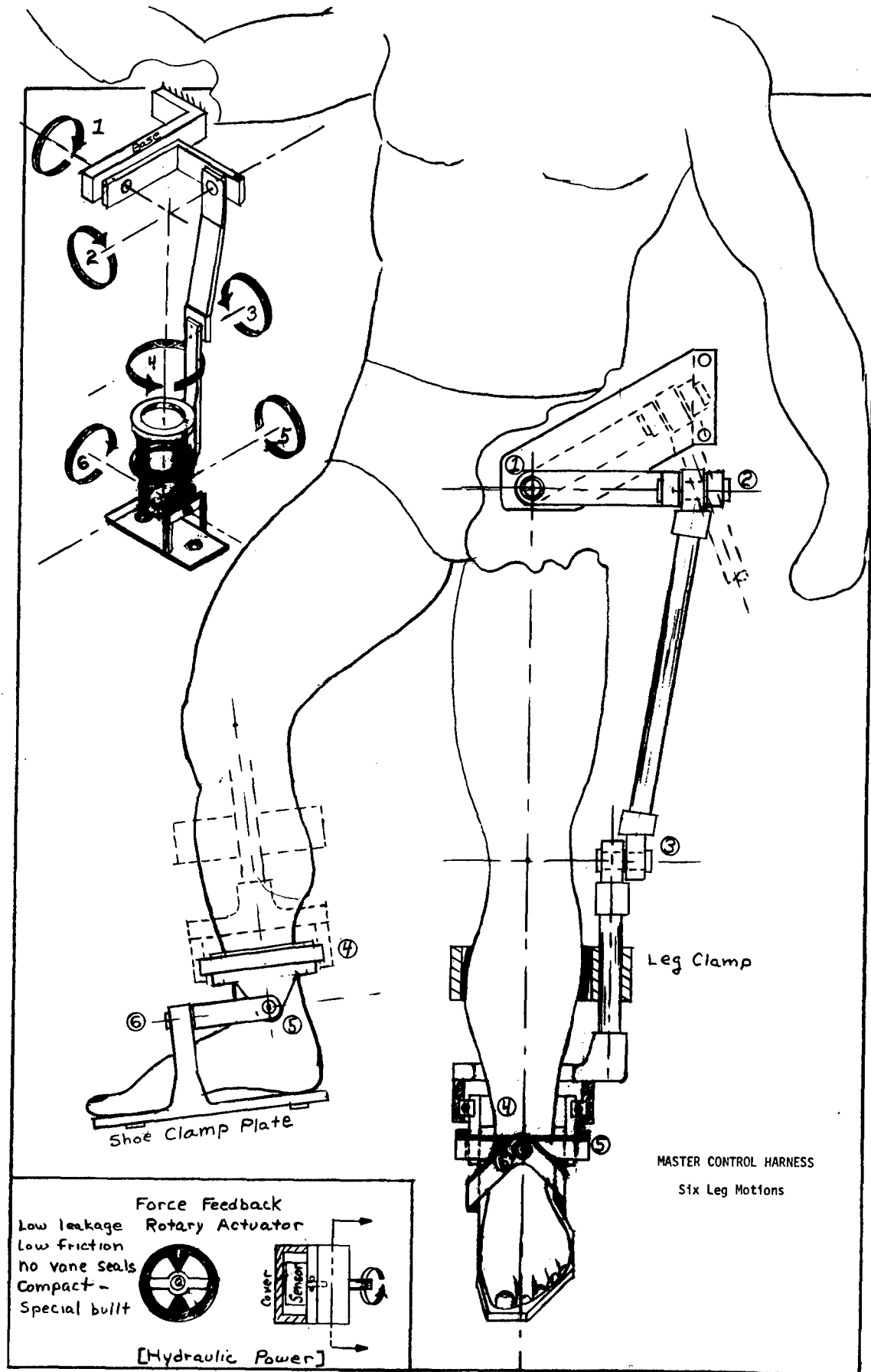
**Figure 17 Arm Master Harness Concept**

to the operator's shoe and the other is the snug fitting clamp around the calf muscle. This second attachment is required to direct control selectively to the hip flexion motion (Number 2) in contrast to knee flexion (Number 3) and vice versa. These two motions have parallel axes which is the reason for the potential ambiguity in control reaction to the operator's leg motions. These two leg attachments also prevent the same problem with respect to the two parallel axes for motions number 1 and 6. An interesting limitation in the amplitudes of the motions exists in order to prevent the development of another redundant pair. If the operator holds his knee straight and pivots his leg forward to a horizontal position, motion number 4 becomes coaxial with motion number 1.

Knee joint should be designed to stop short of straight in-line-over-center conditions. The slight "bent knee" position can correspond to operator's "straight knee" position. This slight desynchronization is not detrimental to operator control sense of position.

Also shown in this diagram is a special miniature hydraulic rotary actuator with a position sensor enclosed. One of the problems in making a harness system like this practical is the packaging of force feedback actuators and position sensors. That, in combination with the necessary electric wire and hydraulic hose, connections tend to make the system rather complicated. To minimize these problems, special small actuator and position sensor combinations should be used. The rotary actuators shown have some very desirable features for this application. Two basic problems with rotary actuators are leakage and seal friction. For this application, a small amount of leakage is not serious since leakage would occur only when forces and high velocities are involved in the control action. During the usual quiescent situation, the pressure is equal on both sides of the vanes and, therefore, power is not lost due to leakage. Without using seals the friction problem becomes negligible, a very desirable feature for this application. Two other alternate approaches are possible: One is to use gearhead motors with synchro or potentiometer position sensors included, and the other is to provide mechanical motion and force transmission

Figure 18 Leg Master Harness Concept

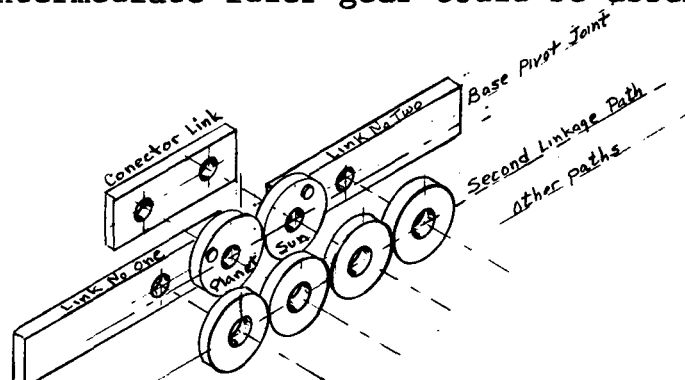


linkages to transmit position and force signals past other motions and to the base of the highest control where weight and size are not as severe a problem. The linkage controls must be designed with differential capabilities so that motions from other pivot joints do not cause interfering motions to the control links passing through that joint.

### Control Linkage and Counterbalance Techniques

As a source stimulant of productive ideas for the designer of force feedback position servo-mechanisms, a series of mechanical control and counterbalance ideas are offered here. Simple, high performance and reliable linkage systems are very important. Close tolerances for the joints should be used in order to prevent backlash or lost motion. Ball bearings should be used for all rotating members. It is surprising how the accumulation of friction in a series of joints adds up to a detrimental amount. Simplicity and compactness are other design factors that are paramount. Some of the illustrations point out simple methods of combining two or more linkage paths with a common routing and yet keeping control action of one circuit independent of the others.

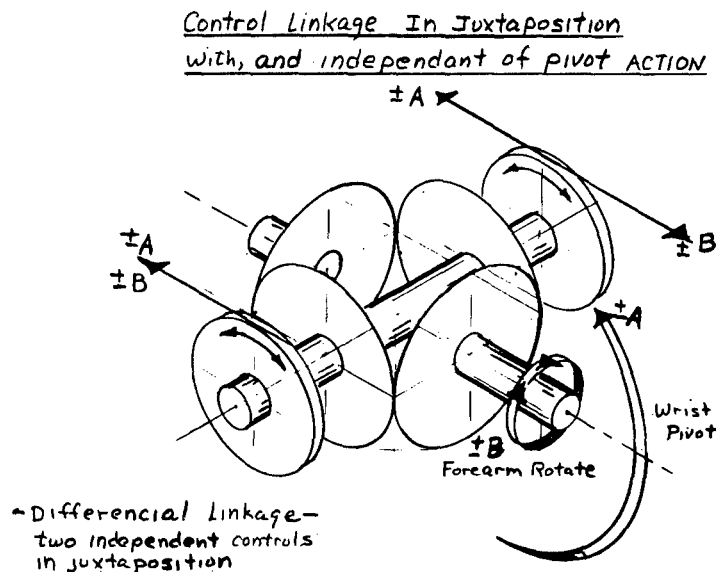
Figure 19 shows a sun-planet gear train combination where one link is driven around the other. The kinematics is such that a second set of gears, assembled in juxtaposition with the sun and planet (and their driving gears), can be rotated independently of the sun and planet gear action. More than two sets of controls can be mounted in this way. It is interesting to note that an intermediate idler gear could be assembled between



**Figure 19 Sun-Planet Gear Linkage**

the sun and planet gears and held by a shaft connected to the connector link. This would provide a pantograph motion where link number 1 and 2 would be held parallel but cause one pantograph link to move laterally with respect to the other. These linkage paths can be continued through a series of joints similar to the one sketched. Cables, steel tape, (anchored to prevent slippage), or fine pitch chain could be used in place of the gears.

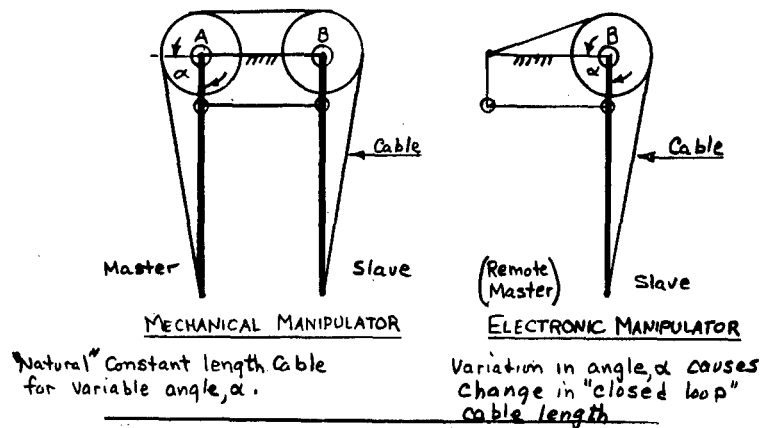
The next illustration (Figure 20) shows a miter bevel gear assembly that allows the passage of a second motion through the basic one of this mechanism. This is



**Figure 20 Bevel Gear Linkage**

a popular mechanism used for the end motions of a manipulator, (forearm rotate and wrist pivot motion). As described in the illustration, rotating the two outer gears or sheaves in the same direction will cause the wrist pivot action. By contrarotation of these two gears, the outer shaft rotates without causing wrist pivot action. The letters A and B indicate motion and the plus and minus signs indicate relative motions of the input-output members.

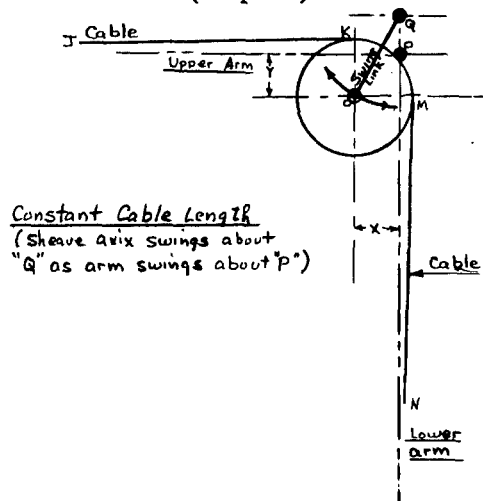
Figure 21 illustrates a design problem involving thin steel tape and sheaves for control. The cable or steel tape must transmit motion and force in both directions



**Figure 21 Steel Control Tape Constant Length Problem**

and therefore must be endless. The closed loop cable is of constant length and is kept tight to prevent backlash or lost motion.

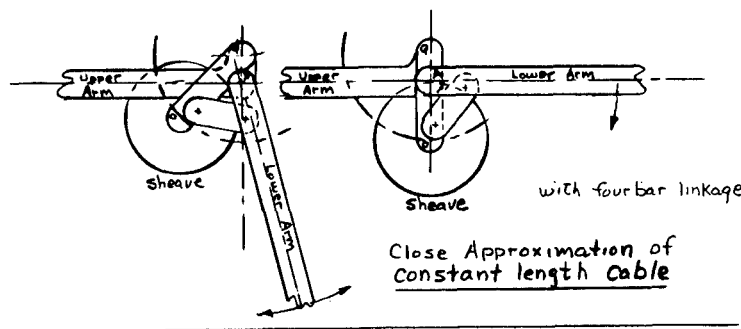
For the schematically shown all mechanical manipulator, the constant length cable is inherently required by the kinematics of the mechanism. The inherent compensation during motion is due to the fact that as the cable unwraps from one pulley an equal amount wraps onto the other pulley. In the case of the electronic manipulator, both master and slave must have a constant length continuous path cable. The sketch shows one-half of the cable system, which is sufficient to illustrate the point. In this case as the angle decreases (Alpha) the amount of wrap on the



**Figure 22 Swing Link for Constant Length Tape Control**

pulley increases, calling for an increase in cable length to maintain a constant force. If the cable length is to remain constant, the pulley center must be moved. There are three simple ways of providing this motion: by use of a swing link as shown (Figure 22), cams, or a four-bar linkage system. Of course, variations of these three approaches are also possible.

In Figure 23 the four-bar linkage concept is illustrated, whose kinematics is a very close approximation to that of a constant length steel tape. This scheme, and that involving the swinging link, are limited to a maximum of  $180^\circ$  of motion. The sketch on the left shows an intermediate position, whereas, the one on the right shows the  $180^\circ$  position.

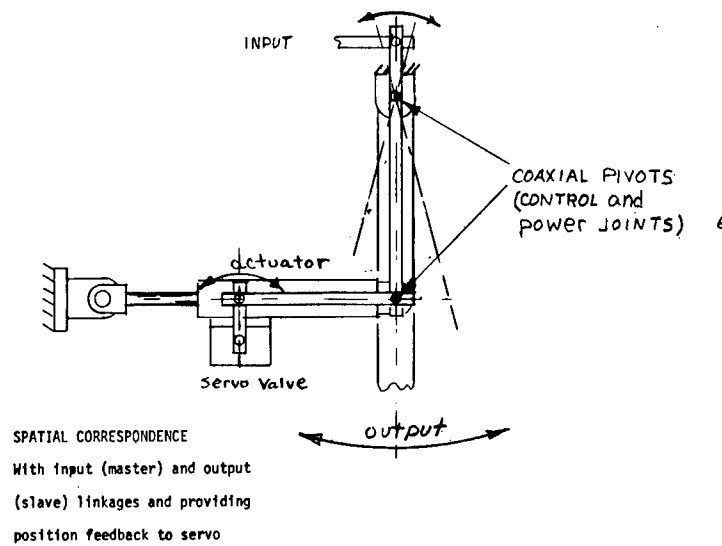


**Figure 23 Four Bar Linkage for Constant Length Tape Control**

In addition to these solutions, there are a multitude of cam solutions possible. Heavy and expensive to build, they are neither discussed nor recommended. Based on weight and cost considerations, the single link is the best solution.

Maintaining spatial correspondence between input control linkages and the responding output member is a prevalent problem for this kind of control. Figure 24 shows a simple approach to the solution of this problem where input and output members are juxtaposed and spatial correspondence is retained. In addition to this relationship, the position feedback to the servo valve is provided





**Figure 24 Master-Slave Correspondence of Kinematics**

in a very simple manner. There are a variety of solutions to this problem. However, it is important to note a key design guideline for achieving these characteristics - certain master and slave linkage pivot joints are coaxial. In this way the sinusoidal action of the bell crank linkages are identical for both sets of links and, therefore, the correspondence of the two linkage circuits is maintained.

### System Counterweighting

As mentioned earlier in this report, for the bilateral force feedback manipulator system any bias forces reflected to the operator are detrimental to performance. The dead weight reflected to the operator decreases his sensitivity to small force reaction signals and constant residual forces reflected to the operator cause fatigue, a serious limiting factor to performance.

It is important to note that the operator can expect to feel unbalanced dead weight forces of the slave as well as the master mechanisms. If the force reflected to the operator from the slave is attenuated by some force feedback ratio, the slave unbalanced force would be reflected with that same ratio of attenuation.

This relationship has a direct bearing on the choice of counterbalancing the slave or master station. Sometimes the restrictions imposed by the operating conditions of the slave station make the solution to the slave counterweighting problem best solved by implementation of the counterweighting at the master station.

Sometimes the performance requirements of the manipulative system are such that a kinematics such as shown for the master harness in Figure 25, can be used rendering counterweighting to a less severe problem. With this scheme, counterweighting is not required unless very large amplitudes of motion are used.

Servo counterweighting is another method for solving this problem. In the case of the manipulator called "Handyman" referred to in this report, servo counterweighting was used. This involved the use of resolvers that signal voltages proportional to the trigonometric

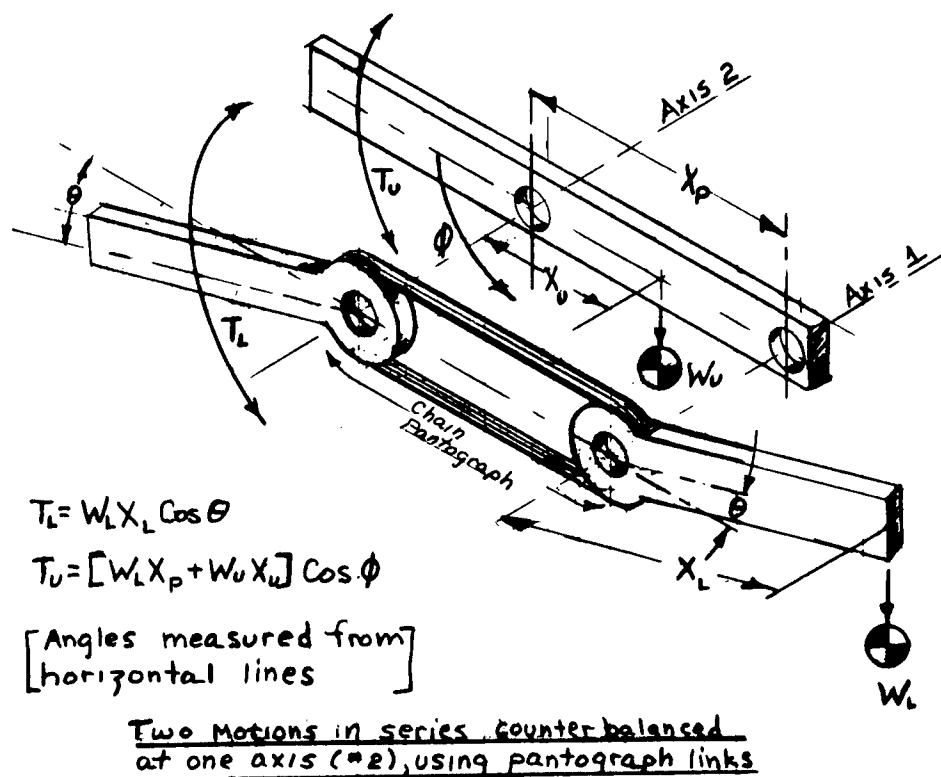


Figure 25 Two Motions Arranged for Spring Counterweighting

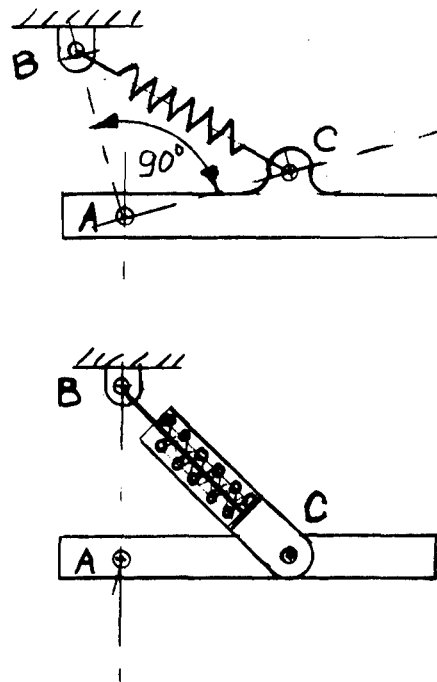
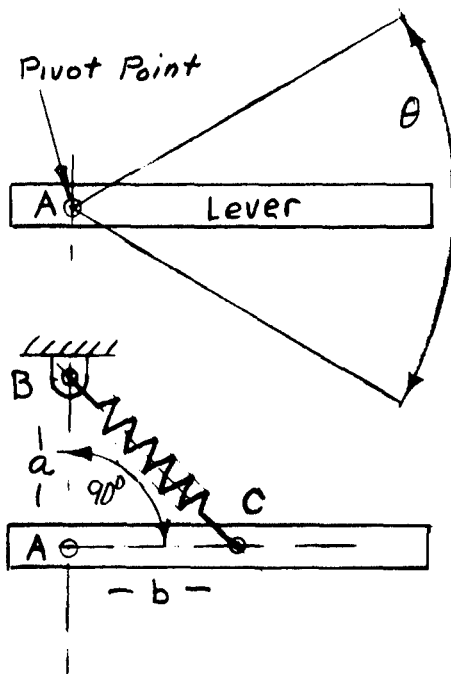
functions related to the motions of the servo system. The servo system then generates a bias force equivalent to the counterweighting torque required for all amplitudes and orientations of this multimotion system. This approach requires a computer arrangement that can provide counterweight values corresponding to the many spatial geometric orientations generated.

A third popular approach to the solution of the counterweighting problem involves the use of springs and special kinematic relationships. In many cases, the motions near the end effector do not need to be counterweighted because of the lesser torques generated by these members. Using this method, spring counterweighting becomes practical. Shown in Figure 25 is a simple method of transmitting two motions in series and torques generated to one common axis. Each of the two motions and torques are reflected at this point, one independent of the other. In this way, counterweighting of each of the motions can be done separately and at a more desirable location.

This approach in control provides the opportunity of using a mechanical counterweight in a practical way. The obvious problem in using counterweights is the cascading effect of weights. Counterweighting one motion requires additional weight to be counterweighted by the second motion in series. In this case, the two motions can be counterweighted without this cascading effect.

Spring counterweighting is a very desirable solution. It is possible to design a spring counterweighting method where exact balance is achieved for continuous rotation of a lever to be counterbalanced. Figure 26 shows the fundamental relationships needed for design of such a system. Four sketches of the lever to be counterbalanced are shown. The upper left picture shows the lever without the counterbalancing. The second sketch underneath this lever shows an arrangement for spring counterweighting. The orientation of distances  $a$  and  $b$  are shown for maximum torque requirements designated as  $T$ . For maximum spring efficiency, length " $a$ " should equal length " $b$ ". The third sketch of the lever shows the

Figure 26 Spring Counterbalancing



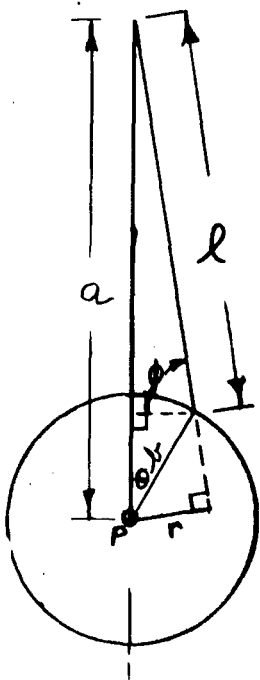
$$T = abK$$

$$F = \frac{T(a^2 + b^2)^{1/2}}{ab}$$

F = Spring force

K = Spring rate

T = torque



Exact Spring Counterbalance  
for continuous rotation

$$l = \sqrt{a^2 + b^2 - 2ab \cos \theta}$$

$$r = \frac{ab \sin \theta}{l}$$

$$X \left[ F_0 + \frac{KX}{2} \right] = T(1 - \cos \theta)$$

$F_0$  = Spring preload force

X = Spring length beyond (a-b)

where T = weight  
times swing radius

counter rotation of the spring counterweight system which indicates flexibility in design arrangements that are possible. The fourth sketch shows that compression springs as well as tension springs are workable. With the use of cable and sheave arrangements it is possible to locate the spring in a more convenient place and transmit the force of the spring through the cable to point C.

In the lower part of Figure 26, the basic mathematical relationships involved in the spring counterbalancing concept are shown. The first two equations identify the simple trigonometric relationships while the third equates the spring energy to the energy of the weight to be counterweighted.

These fundamental mechanism designs are presented as examples of answers to prevalent design problems related to master-slave control designs. They are not all encompassing and many more approaches are possible. The concepts also serve the purpose of indicating problems that are encountered in designing this type of equipment.

## QUADRUPED TEST BED DEMONSTRATION AND RESULTS

### Development Program Synopsis

This section is devoted to the description of the quadruped test bed research program conducted by the General Electric Company for the U. S. Army.

The development of the quadruped test bed began on 29 June 1962. Research work continued for eight years and the completed quadruped was delivered to TACOM, Warren, Michigan in August 1970.

The first phase of this program was a feasibility study of a levered vehicle. This program was initiated in March 1962, and was completed in April 1963. The contract number for this phase of the work was DA-19-020-ORD-5729. The second phase was for the design, fabrication and test of a limited motion pedipulator. This program was designed to show that man can balance such a full scale machine, and to illustrate the practicability of the control mechanism. The contract number for this work was DA-36-034-AMC-0268T. The test and evaluation part of this program was done between 8 April 1965 and 28 February 1966. The third phase, February 1970 - August 1970, was aimed at the development of an ambulating quadruped test bed. The contract number for this work was DA-20-113-AMC-09225(T).

### Description of Feasibility Study of a Levered Vehicle

The purpose of the feasibility study was to examine the possibility of the development of a full size, man operated, quadruped test bed vehicle. The work included the following: establishment of preliminary performance criteria; analysis of perambulation; and human factors analysis.

Investigation of the characteristics required of the servo system needed for this quadruped test bed indicated

that the required technology was within the state-of-the-art and that the man-controlled levered vehicle concept was feasible. Two basic questions remained unanswered: (1) Is the sensory and psychomotor task requirements imposed by a walking levered vehicle within the scope of man's capabilities; (2) What is the optimum man-machine linkage with respect to efficient and effective man-machine coordination.

The second half of the feasibility study was directed toward the objectives related to an engineering analysis of a full size, man-operated, levered vehicle. As a result of this portion of the study, performance requirements, configuration, size, weight, control characteristics and power requirements were defined. The conclusion of this analytical study was that the levered vehicle was feasible and a vehicle concept was recommended. Even though the general conclusion was that the walking levered vehicle was feasible, experience with a full size agility demonstrator was deemed necessary before design and fabrication of the powered quadruped was recommended.

It was decided to design and fabricate a full scale, limited motion pedipulator for experimental study.

The machinery built for this program was not intended to be unabridged demonstration of a walking machine. Rather, it was needed to establish whether a man could perform the most crucial part of walking: balancing. Subsequent experiments demonstrated a practical system that exposed key technical points of concern: practical servo-mechanisms, effective operator control methods and easy achievement of balance and torso posture control. Figures 2, 15 and 16 show photographs of this balance demonstrator. It is 18 feet high and has two powered motions. One represents ankle motion which allows the operator to swing the demonstrator to-and-fro to balance the machine at the ground level. The second motion is a torso motion which allows comparable hip motion bending to-and-fro in the same plane of action provided by the ankle balance motion. The balancing experiment proved very successful. Over 60 people, varying from astronauts to secretaries, balanced this machine in a matter of a few minutes of learning time for

each person. This early success substantiated the practicability of coupling man to machine with force feedback and spatial correspondence control. Furthermore, the response of the hydromechanical servo system proved to be more than adequate for the quadruped test bed concept.

Acquiring the ability to balance was a dramatic "moment of truth". The operator's head was 15 feet above the floor. Some people refused to try the machine because of the height. Every operator who started to balance was apprehensive and understandably cautious. But, in almost every case, the operator quickly learned that he was in complete control and could balance easily and effortlessly. A few people were nervous and tense because of the height and, therefore, did not adapt proficiently. The key to good control is to be relaxed and to respond naturally to the human neural signals.

The second half of this balance experiment involved test and evaluation, for the purpose of defining design guidelines for the development of a walking test bed.

At this juncture the development of a two-legged walking test bed having nine feet long legs with degrees of freedom in each leg was recommended by TACOM and the General Electric Company.

However, after many conferences with the other sponsoring agency, ARPA, it was decided that a quadruped would be more relevant to future Army requirements.

The next phase of the research program was the development of the ambulating quadruped test bed. It covered a program for the development, design and fabrication of a full scale walking machine and identified as an "Ambulating Quadruped Transporter".

The design objectives for the proposed walking mechanism included transporting a payload of 500 lbs. at speeds up to five miles per hour over rough terrain. In preliminary concept, the machine was planned to have four legs, six feet long, and be 10 feet high and  $3\frac{1}{2}$  feet wide, with four feet of ground clearance. Each leg would have a minimum of



three powered motions to enable the operator to direct the movement of the test bed through his natural arm and leg motions. These design goals were specified to assure practical development of man-machine technology.

In August 1970 the completed ambulating quadruped transporter was delivered to TACOM, Warren, Michigan.

The following discussion of this program delineates significant highlights and comments on salient aspects of the work.

Preliminary work done up to 20 May 66 included human factors studies relative to the legs master control and related man-machine mechanization concepts.

A full-scale simulator was built to evaluate man-machine relationships and machine kinematics (Figure 27). The simulator was unpowered, but the controls were mechanically connected to the machine's legs to simulate force feedback and position spatial correspondence. During operation the simulator was suspended from a crane and the operator executed walking and turning maneuvers. The crane allowed light touch control of vehicle by ground contact. Human factors analysis of simulator tests indicated that satisfactory control of all leg motions could be accomplished by a single operator. A very critical and difficult problem solved was the establishment of the operator location, orientation and method of support.

By November 1966, the form and design of the powered quadruped test vehicle had been defined, and operator position and control arrangements were established. Servo analysis work and breadboard testing was in process and power supply requirements were defined by then.

It was decided that each leg would have only three basic motions; two in the hip and one for knee flexure. It was known that care had to be taken not to allow the knee to go to a straight over-center lock position. In this position knee joint torque is not generated by the

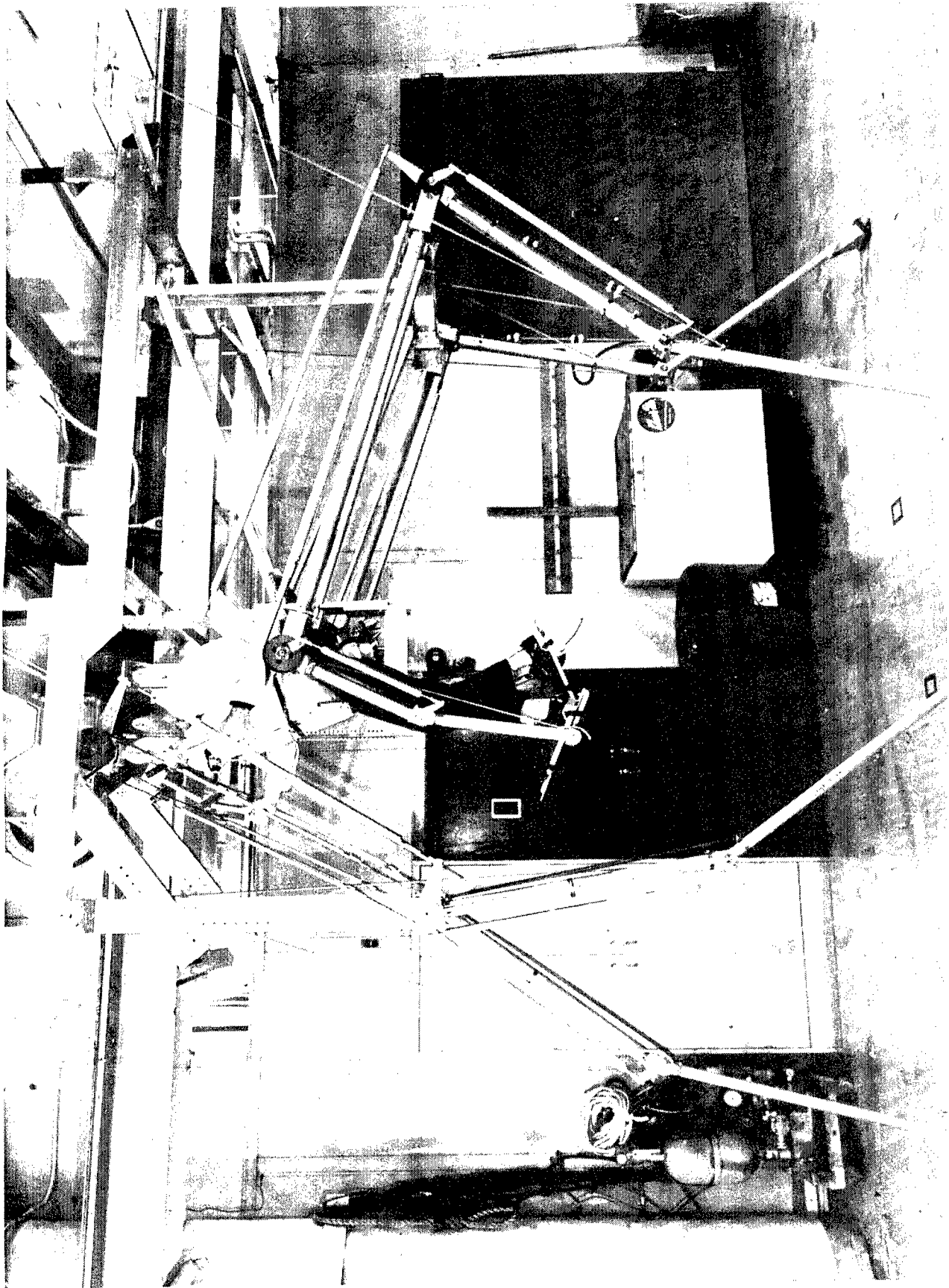


Figure 27: Quadraped Kinematics Simulator

pressure of the foot on the ground. In this situation, kinesthetic force information is not reflected to the operator. Although there are only three motions in each of the four legs, it was found that smoothing of the walking gait would be enhanced by the reflection of human leg and pelvis motions through the three motions in each of the mechanical legs. It was predicted that the walk would be clumsy, but adequate to prove feasibility of the walking levered vehicle concept.

The servo technique used is very inefficient; however, it was the best choice achieving the required servo performance minimizing the cost of components and machine design complications. The basic reason for the low power efficiency is that the power controlling components were fed from a constant pressure source. If a variable displacement pump had been used for each of the servo valves (and the command for power from the pump was primarily a function of flow requirements rather than pressure of the servos), the system would have been much more efficient because pressure would have been generated only to the level needed for any work condition.

Because of the inefficient servo power consumption requirements, the power supply was very large and it became questionable whether the power supply would fit within the specified confines of the quadruped chassis. The attempt to mount the power supply in the test bed failed and a separate self-contained power supply was used to operate this test vehicle. This change in location of power supply did not limit the performance, test and evaluation required for this program.

By May 1967 the design was nearly complete and fabrication was in progress. Extensive servo analysis and laboratory test work had been done by this time. Difficulty was experienced in establishing low friction and low viscous drag servo control characteristics where all hydromechanical components were used. Special servos had to be developed which included special internal stabilizing techniques. This was both expensive and time consuming.

By 15 May 1968 the assembly of the vehicle was completed and all preliminary tests of components had been finished. The most significant milestone was 26 April 1968 when the quadruped test bed was lowered to the floor level and the servos controlled the four legs successfully.

By November 1968 the feasibility of the ambulating quadruped transporter had been proven and demonstrated. However, a great deal of trial and error type work remained to be done, which included the readjustment of the linkage proportions, the force feedback ratios and the operator's location to optimize the performance of the man-machine system.

The machine was successfully demonstrated to do many maneuvers which included basic actions of walking, turning, backing, climbing, threading between obstacles, moving obstacles and even operating the machine with the operator blindfolded.

The following are significant operational tests which were achieved with the quadruped test bed:

- With the precision operator mimicking control of the quadruped legs and force feedback to the operator, the operator was able to maneuver a pseudo bomb and line it up precisely with two hanger pins which is equivalent to hanging a bomb on the underside of an airplane wing.

- The quadruped climbed with the front legs onto a pile of timbers five feet high and was able to knock them down one at a time.

- With a special attachment on a front foot, the quadruped picked up a 500 lb. weight and loaded it into the back end of a M151 Truck.

- The walking machine was able to push the M151 out of a mud hole and over a barricade.

- The quadruped was walked through an obstacle course with 525 lbs. of timbers strapped to it.

• The quadruped was used to drag a 1200 pound wooden framework across dry sand.

• The operator could maintain balance of the quadruped on two diagonal feet showing the ability to respond very effectively to his vestibular cues.

• Figure 28 shows the master control arrangement and operator position. This arrangement was the result of much test and analysis work in regard to the psychophysical factors related to this type of control work.

Learning to use the two front legs was easy because the operator was able to see the legs move. But, learning to use the rear legs was difficult. The operator could not see these legs, and hence, to develop a mental image of relative position of the machine's rear legs as compared to the operator legs. Deviation in spatial correspondence and amplification of mechanical to operator leg motions required learning especially in respect to proprioceptive sensing of position.

The five to one amplification of operator motions reflected to the quadruped legs is not confusing where there is spatial correspondence between the input and output effectors. This is a very important and easily learned relationship and it is mastered through the experience of the human proprioceptive sensing functions. Once this is learned, the operator operates the slave system with a mental transference that lets him easily perform as if the output mechanism was merely an extension of his own appendages. This is a very important consideration in the design of this kind of equipment. Emphasis is placed on the comparison of learning ability with respect to front legs and rear legs, to show that the lack of visual monitoring slows down the learning process. Ultimate proficiency is limited also.

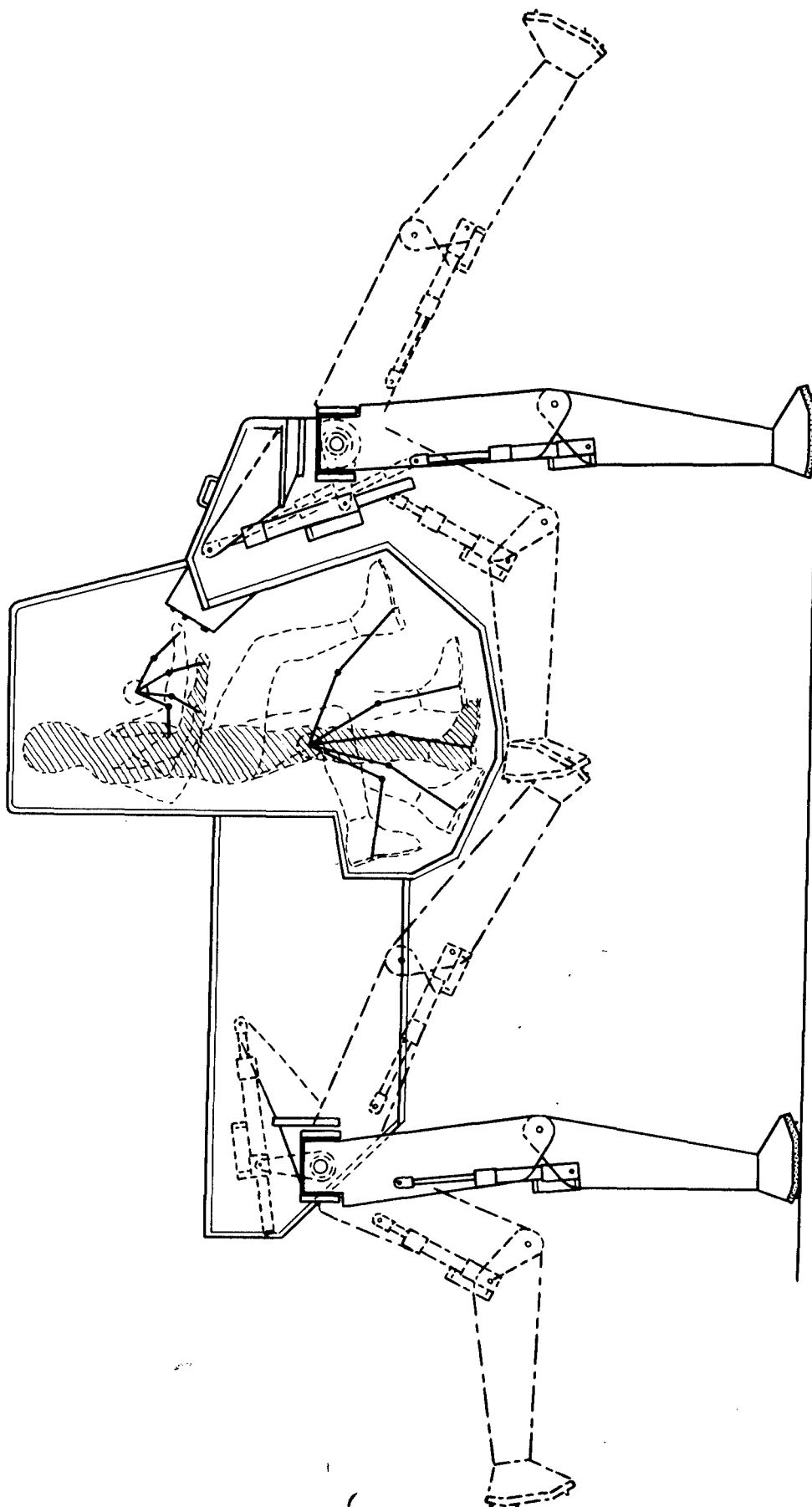


Figure 28    Quadruped Master Control and Operator Position

### QUADRUPED TEST BED EXPERIMENTAL RESULTS

- A measure of force feedback servo-mechanism potential for man-machine systems -

We have described the development of a 3,000 lb. walking test bed in the preceding chapter. Developing simple, rugged force feedback mechanisms and techniques for this extremely challenging test equipment was the harbinger of many new man-machine concepts that may show promise for the solving of some of the Army mobility problems.

Preliminary tests were made for optimizing control characteristics such as force feedback ratio, operator position and support, and operating procedures and techniques. The second phase of tests was designed to demonstrate basic maneuvering capabilities of the complex man-machine systems. The third phase of testing explored the usefulness of a walking machine in performing practical tasks.

The general concept configuration and control relationships are illustrated in Figure 28. The legs reflect position and forces back to the operator with spatial correspondence maintained between operator and machine.

The Quadruped is a very significant and dramatic machine to demonstrate the potential of the man-machine control, when one realizes that the operator's neuromuscular reflexes direct twelve position servos simultaneously and in harmony. In contrast to this type of control, previous programmed or fixed walking gaited vehicles required a complex control system to achieve diversity in maneuvers. The results of such experiments with programmed-type controls showed very limited potential to this kind of approach in control of multimotion machines. But, when the controls reflect both force and position of the load with spatial correspondence, the machine becomes in effect a rational extension of the man.

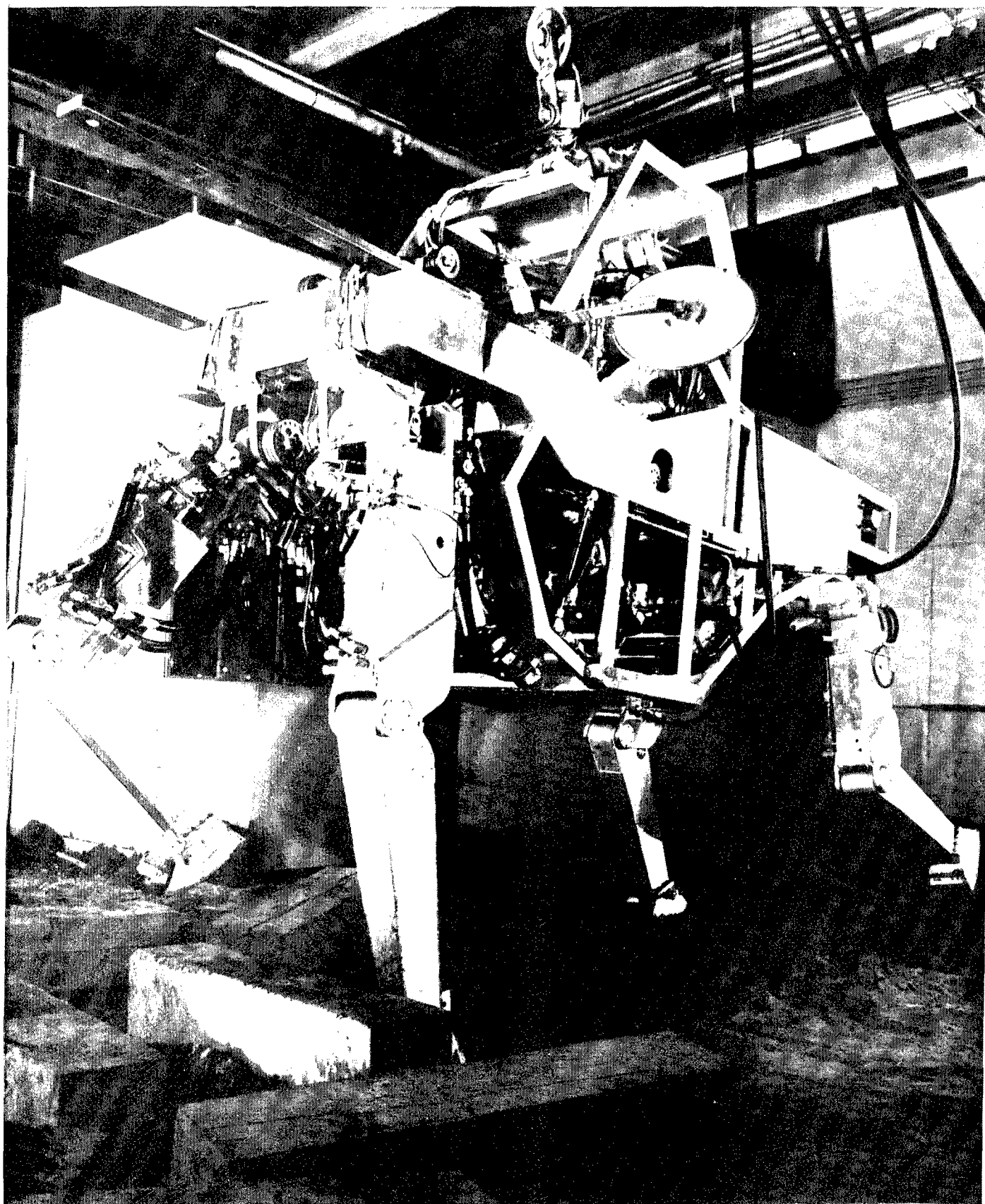


Figure 29: Quadruped Balance on Two Legs



## Walking Machine Description

The four-legged walking machine shown in Figures 28 and 29 is capable of housing an operator and control equipment. This test bed is 11 feet 7 inches long; the legs are 6 feet 7 inches long, giving an overall height of nearly 11 feet. Each leg incorporates three motions - two in the hip and one in the knee. The force-reflecting servos necessary to move the machine are powered by a special motor and pump system. The rear legs respond to an operator's leg action; the front legs respond to the motion of the operator's arms, as shown in Figure 28.

## Control

This control requires an operator to go through the ambulating and balancing motions because the machine is built to follow or mimic the operator's motions. With power boost to the machine, the reflected position and force information from the machine's feet to the operator, the operator can easily cause the machine to respond as if it were merely an extension of his own appendages. His visual, vestibular, proprioceptive, kinesthetic and tactile sensing mechanisms are able to effectively direct the operator's neuromuscular reflexes to respond to these bilateral servo-mechanisms.

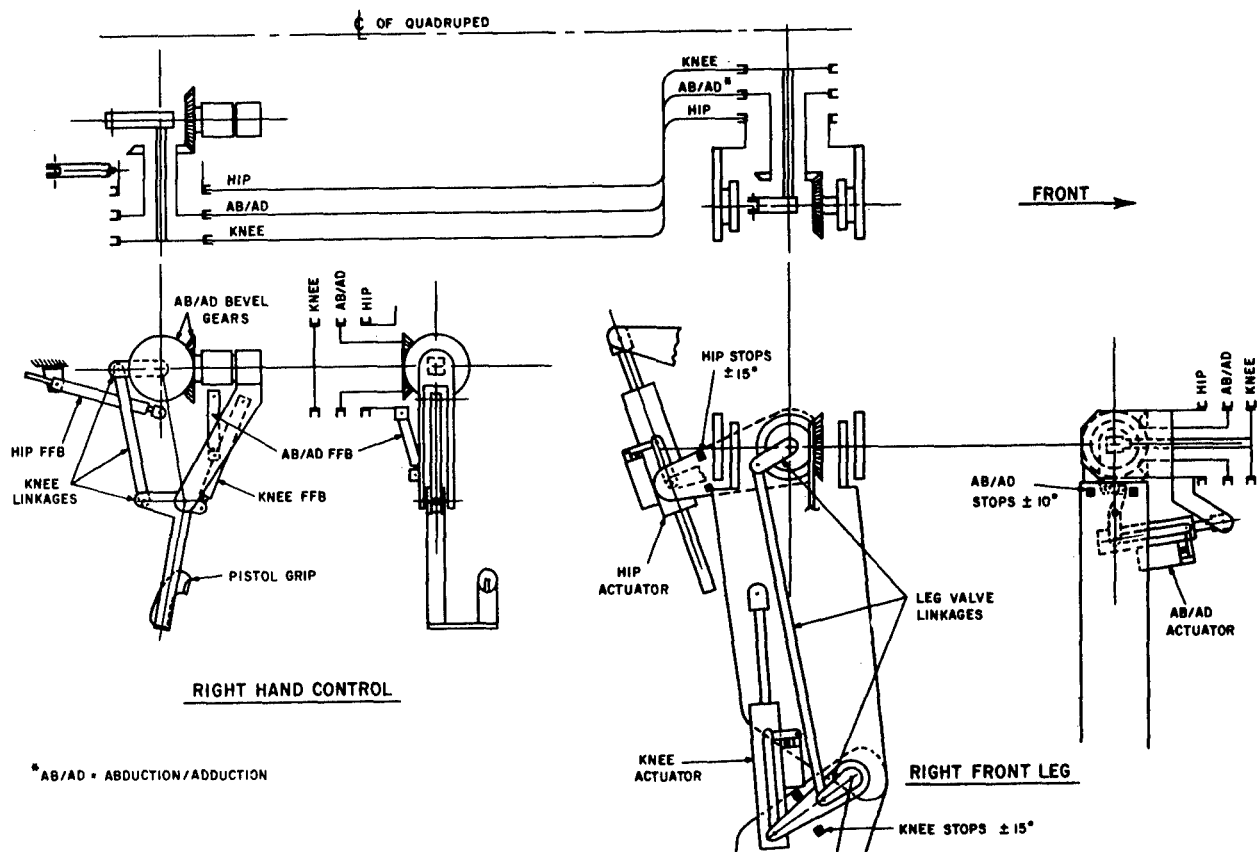
As previously noted, three motions are provided for each of the four legs (two in the hip and one in the knee). The foot can exert a nominal 1,500 lbs. of force in any direction and much higher forces in some cases, depending on the knee flexure angle. Forces reflected to the operator are one part of 120 generated at the machine's foot. This means that the force reaction ratio to the operator is one part in 120. The ratio can be varied to optimize operator effectiveness control. The primary consideration in varying the force ratio is minimizing the amount of energy or work required by the operator and the amount of force needed to provide crisp and sensitive control information to the operator.

The servos are hydromechanical and do not require electronic elements. They are bilateral in that both the

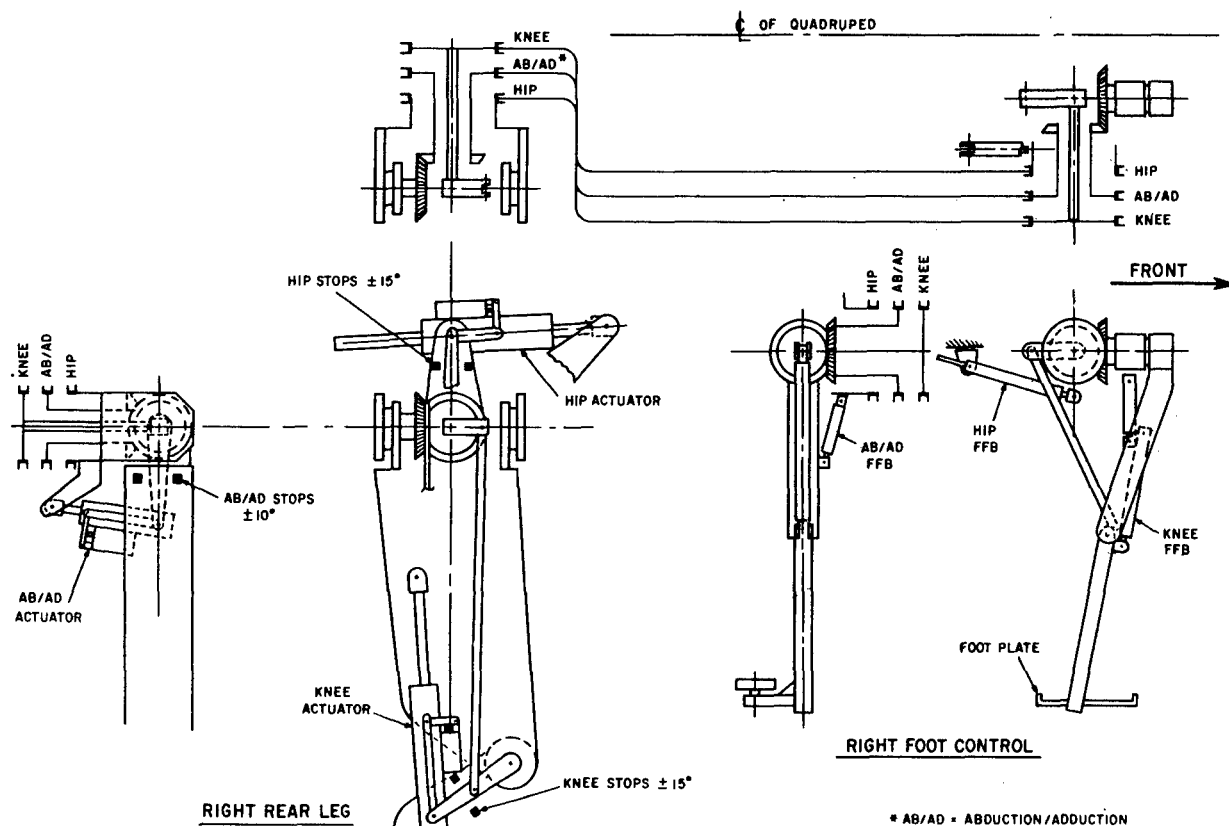
operator end and the output end respond to position and force information. This means that the electrohydraulic servo valves and mechanical linkages must have the ability to a reversal in force, position or energy flow direction. This control method can be called "cybernetic" because motion and force information are transmitted between the machine and the operator.

### Hand Controls

Two hand controls, right and left, control the right and left front legs of the quadruped respectively (see Figures 30 and 31). Each hand control provides geometric and force patterns that are reflected at higher proportional values to the quadruped leg (i.e., it includes a hip joint, a thigh and a lower segment). The termination point is a pistol grip. The operator and quadruped leg lengths retain correspondence and orientation. Small hydraulic actuators are mounted on the controls. With each motion, the actuators reflect independently a force proportional to the force in corresponding actuator on the leg.



**Figure 30      Quadruped Master Arm Control Harness**



**Figure 31 Quadraped Master Leg Control Harness**

Mechanical stops have been added to the controls 5° beyond the required motion of the quadraped leg (i.e., the hip flexure for the control is 75° forward and 25° rearward as compared to the machine leg motion of 70° forward and 20° rearward, etc.).

### Foot Controls

The right and left foot controls provide inputs to the corresponding quadraped rear leg servo valves and control the three powered motions of each leg. These foot controls are similar to the hand controls. The linkage length proportions are different to accommodate the biomechanics of the operator's leg and the operator's position in the control station of the quadraped. The

lower leg segment is longer and terminates in a receptacle for receiving a shoe pad which is strapped to the operator's boot prior to entering the control station. This arrangement gives added flexibility for assorted shoe sizes and styles that will fit the controls. Moreover, it allows rapid connect and disconnect without requiring an operator to reach his feet with his hands, an impossible maneuver while strapped in place.

### Operator Suspension

The operator must be supported to minimize relative motion between himself and the vehicle. He must be supported properly so that in the process of activating the quadruped the acceleration forces he is subjected to will not cause him to be unsteady to the point where he cannot adequately direct the quadruped motions. Optimum support allows him to effectively interpret vehicle motions and make balance and maneuvering actions with confidence and reliability. After extensive study and testing of different operator positions, it was decided the best position is obtained when the operator sits in a vertical attitude. This solution represents a compromise because the operator is not oriented in the same attitude as the quadruped. To have similar orientation the operator would have to be in a position of crawling on all fours. It was found that the prone position would be very awkward, tiresome and would limit the operator's ability to maneuver his controls (see Figure 27).

The seat is adjustable fore and aft, up and down, and in tilt. The back support is hinged so that good operator support is maintained for various tilt positions of the seat. A pelvic pad provides support fore and aft by hinging the ends of the support to form a clamshell arrangement. With straps added to the sides of the pelvic pad and extended to the cab, complete stabilization at the hip level is possible. It is very important to oppose control perturbations.

To assure adequate support and reduce fatigue, provision has been made for the addition of shoulder straps. These straps are attached to the clamshell pelvic support at one end and to the bulkhead behind the operator's shoulders at

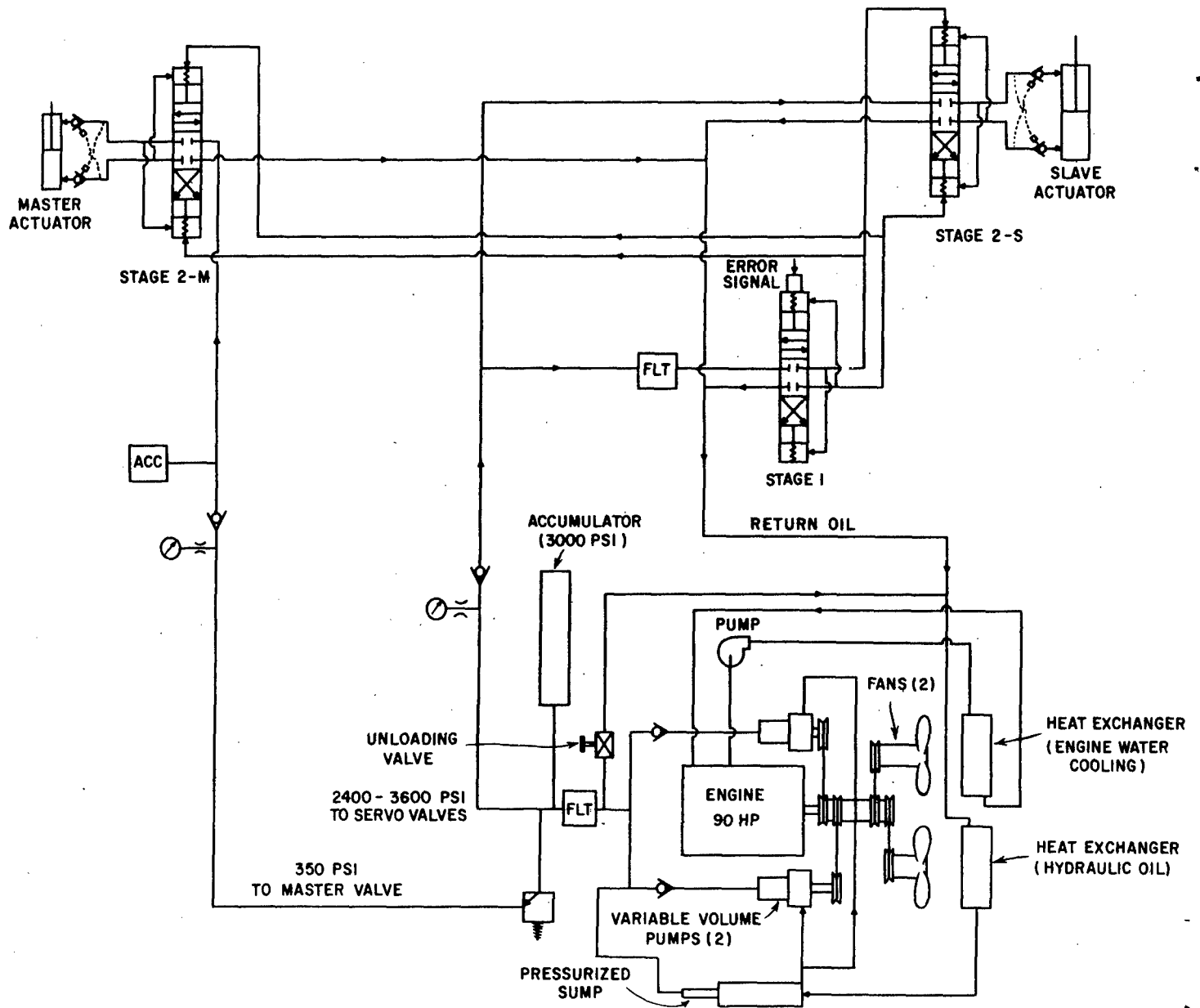
the other end. Automobile seat belt buckles are used to provide simple buckling procedures.

### Power

Servo-controlled, high pressure oil is used to drive hydraulic actuators located on each leg of the walking truck. These actuators are the "muscles" for the three powered motions (i.e., hip flexure, knee flexure and abduction/adduction flexure). Oil input to the actuators is regulated in direction, quantity and pressure by servo valves that respond to operator hand and foot controls. In order to provide oil of sufficient quantity and pressure, a vehicle power supply is required. The vehicle power supply consists of a gasoline engine, hydraulic pumps and hydraulic accessories, such as heat exchangers, an accumulator filters, shutoff pressure regulator and safety valves etc. (see schematic of this system in Figure 32). The capacities of these components have been determined by detailed analysis of both static and dynamic conditions of the quadruped during maximum effort and of the requirements stemming from the stipulated 5 mile per hour walk mode. From this analysis it has been determined that a 5 mile per hour walk can be provided by an oil flow of 50 gallons per minute at 2400 psi, which requires 80 horsepower delivered to the pump. A pressure of 3240 psi was made available for maximum force efforts at lower speeds.

The power supply required for this operation does not indicate the amount of power needed for a multiple motion servo system. As mentioned before to keep development costs down, a constant pressure single source pump system was supplied. For optimum efficiency a variable displacement pump should be used for each servo circuit. The pump regulation would supply high flow at low pressure for free swinging leg action and for low volume or slow motion high pressure or high force to the leg. With the constant pressure source for this quadruped test experiment, all rapid free-swinging motions with low force requirements are generated by hydraulic flow from a high constant pressure source. This represents significant inefficiency in terms of power but in terms of experimental costs it was an expeditious choice.

Figure 32 Quadruped Power Supply Circuit



## Design Limits

To keep development costs at a minimum, machine requirements were restricted to provide no more than adequate maneuvering. The three motions in each leg are limited in amplitude -- there are no ankle motions or leg twisting actions. In comparison, the human leg has eight distinct motions and these are complemented by three additional motions provided by the pelvis.

An amputee with a wooden leg walks with a limp and, of course, the limited motions of the walking truck would cause crude perambulation. The quadruped is stiff legged in nature and has a rough gait; however, the machine leg responds to the human leg motion which is an integration of many major human leg motion determinants. In other words, the quadruped walking motion patterns are much smoother than would be expected normally from a machine such as this with limited leg motions. The articulating human leg motions are exaggerated in the three basic motions of the quadruped leg to create smooth walking of the quadruped. This causes the gait to be smoother than a three-motion leg "should be". The three motions were sufficient to prove the feasibility of walking and, for the purpose of this program, more than three motions would have been unnecessary. There is a risk, however, that the people who have an opportunity to employ this new control technology may underestimate the potential represented.

## Test Experience

Early walking experience was gained cautiously with the use of a traveling tether for safety. After initial experience was successfully built up, the quadruped was actually walked outdoors over irregular terrain, proving that a high degree of control can readily be attained.

Each leg has adequate power, speed, torque and several positioning accuracies. During the test period, the man-machine relationships have been refined as follows:

- Forces reflected to the operator were increased.
- Viscous drag in the servos was reduced.

- Relative torque values of each motion in the controls were adjusted to conform with human biokinesthetic torque proportions.

- Hand grip orientation and relationship to control kinematics were changed.

- Seat position was modified.

- Operator leg counterweights were incorporated.

- Servo static bias forces were eliminated.

- Positions of the master controls relative to the slave legs were accurately synchronized.

Each of the eight adjustments was important to provide adequate integration of man and machine. It is an exacting situation where the total human factor relationships must be properly adjusted to provide the operator with the ability to communicate and respond without serious difficulty. The operator must simultaneously control twelve position servos and respond readily to twelve force inputs from the machine's legs. Refinements such as those listed above have significantly affected the operator proficiency because of the multiplicity of motions and operator sensitivity to any of the slightest incongruities in the required human characteristics and functions.

To walk well with this machine, the operator requires a training period. The machine's time constants and responses to the large forces are not the same as those in the human body. Both hand and leg motions are amplified four times. Also, the operator does not have tactile force sensations from the bottom of the truck's feet. Sitting in an upright position, the operator is not oriented horizontally or prone, to simulate the machine's walking attitude. He feels forces considerably less than those he normally experiences from the weight of his own body.

### Learning Power

The most critical concern with respect to operability was the problem of operator sensing and responding ability



to the rear part of the chassis and the rear legs. These parts were out of sight and, therefore, the leg and chassis pitch and yaw action was expected to be difficult to interpret by the operator. This concern was a valid one. Initial efforts to walk revealed these problems. Mirrors were used as a training device. Walking without these mirrors was impossible during preliminary learning experiences. The transition of dependence on mirrors to human subconscious proprioceptive sensing of position was sudden and yet subtle. The learning power through this human attribute is unusually high.

Complementing this muscle position memory system, the neuromuscular reflex system learned to comply to the force vectors at the four controls in a harmonious way. These two educated human functions combined with visual and vestibular sensing of balance allowed the operator to control the quadruped easily naturally and with confidence after a relatively short training period.

It is interesting to note that this unusual and successful union of man and machine represents the man's ability to adapt and use this machine as an extension of his own body even though there are many distortions in this anthropomorphic device. Man can adapt to many distortions. The extent of distortion that is reasonable to cope with depends on salient factors such as: Amount of operator training time allowed; complexity of the machine function and the operation; the operator endurance and work cycle and the efficiency of performance needed.

The man in total, represents the nervous system of a four-legged animal. The machine can be thought of as the biomechanical part of the animal. Thinking of the man-machine relationship this way, one should expect successful adaptation of the man to this machine concept. The foot is awkward until his neuromuscular sensors are trained. It is reasonable to expect that a functional quadruped can be maneuvered with the effectiveness of an animal.

#### Maneuvering Tests

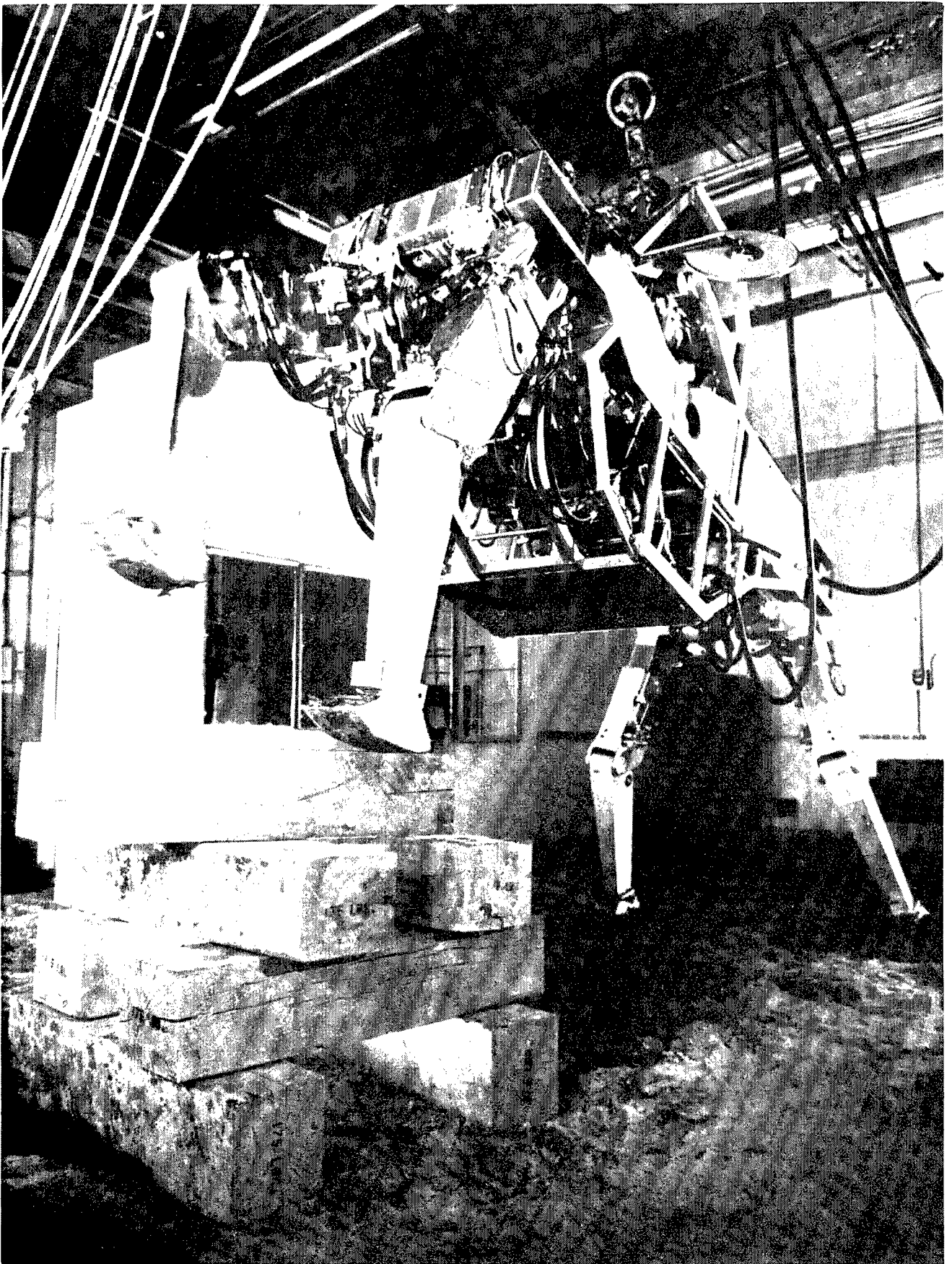
After 15 hours of training time, an operator can perform many experiments in maneuvering the walking test bed. The

feasibility of the concept was shown by various experiments:

- Walking forward, backward and blindfolded.
- Turning around.
- Balancing on all combinations of three legs as well as diagonal pairs of legs (Figure 29).
- Climbing a four-foot obstacles (Figure 33).
- Walking a narrow pathway.
- Weaving through patchwork obstacles.
- Lifting the back end of a M151 vehicle out of a mud hole (Figure 34).
- Placing the front feet in a M151 vehicle and pushing it back and forth.
- Skidding a 1,000-pound load across a floor.
- Lifting a 500-pound load with one front foot (pintle mounted on foot) and placing it in a M151 vehicle.
- Hang a pseudo bomb on simulated hanger lugs beneath an aircraft wing (Figures 35, 36 and 37).
- Carry a load equal to 500 pounds.
- Balance the front legs on a large teeter board (similar to a bongo board).

The pseudo bomb loading example shows ability in accurate orientation and manipulative capabilities. The machine had two prongs on the front of the chassis. Each prong had a hole which had to be lined up with two vertical mating pintles. Next, the bomb had to be lifted and connected to two hanger lugs that required straight line translation for a distance of ten inches while the bomb was held horizontal. The horizontal axis was normal to the direction of hanging motion.

Figure 33      Quadruped Climbs Over Blocks



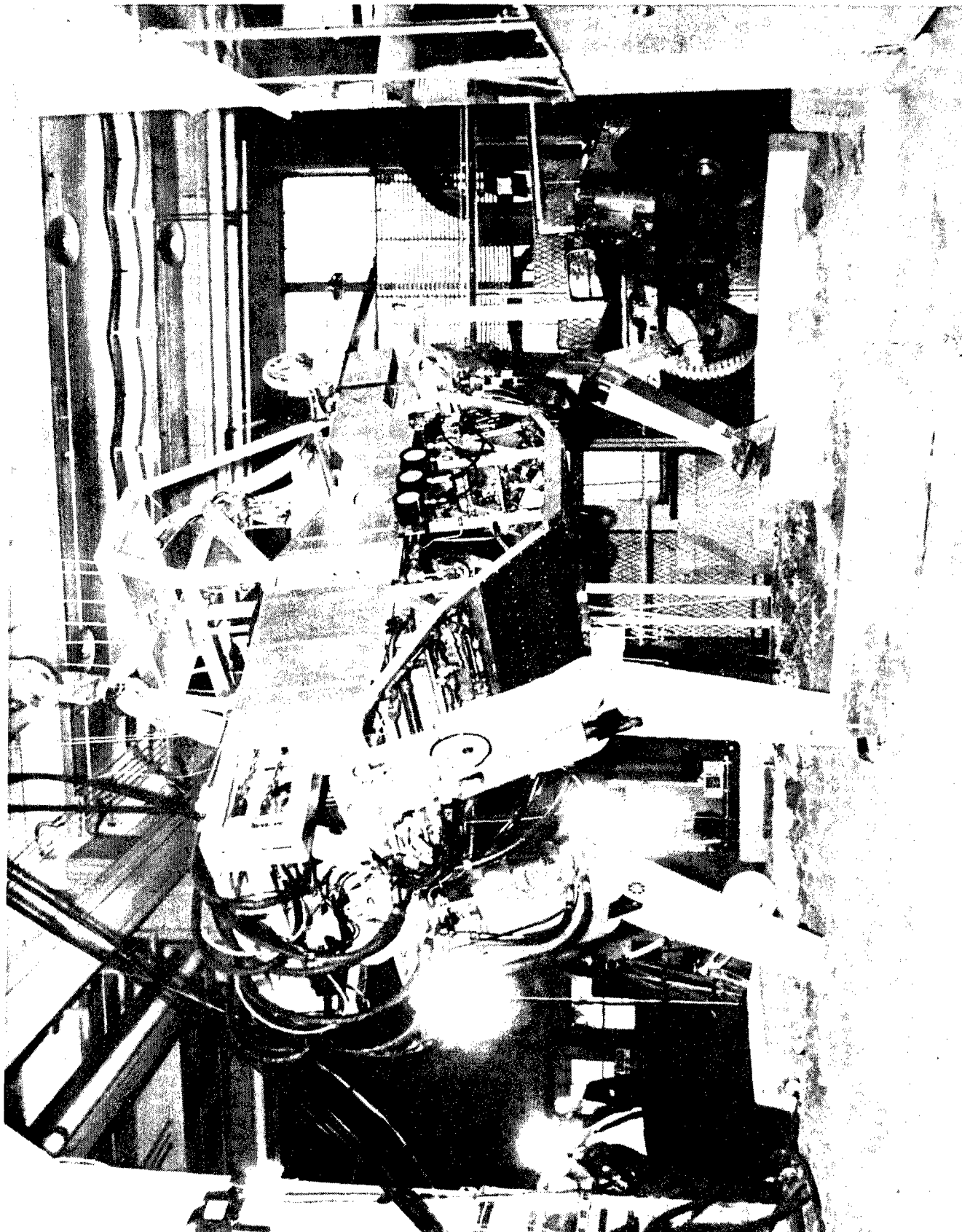


Figure 34: Quadruped Picks Up Jeep

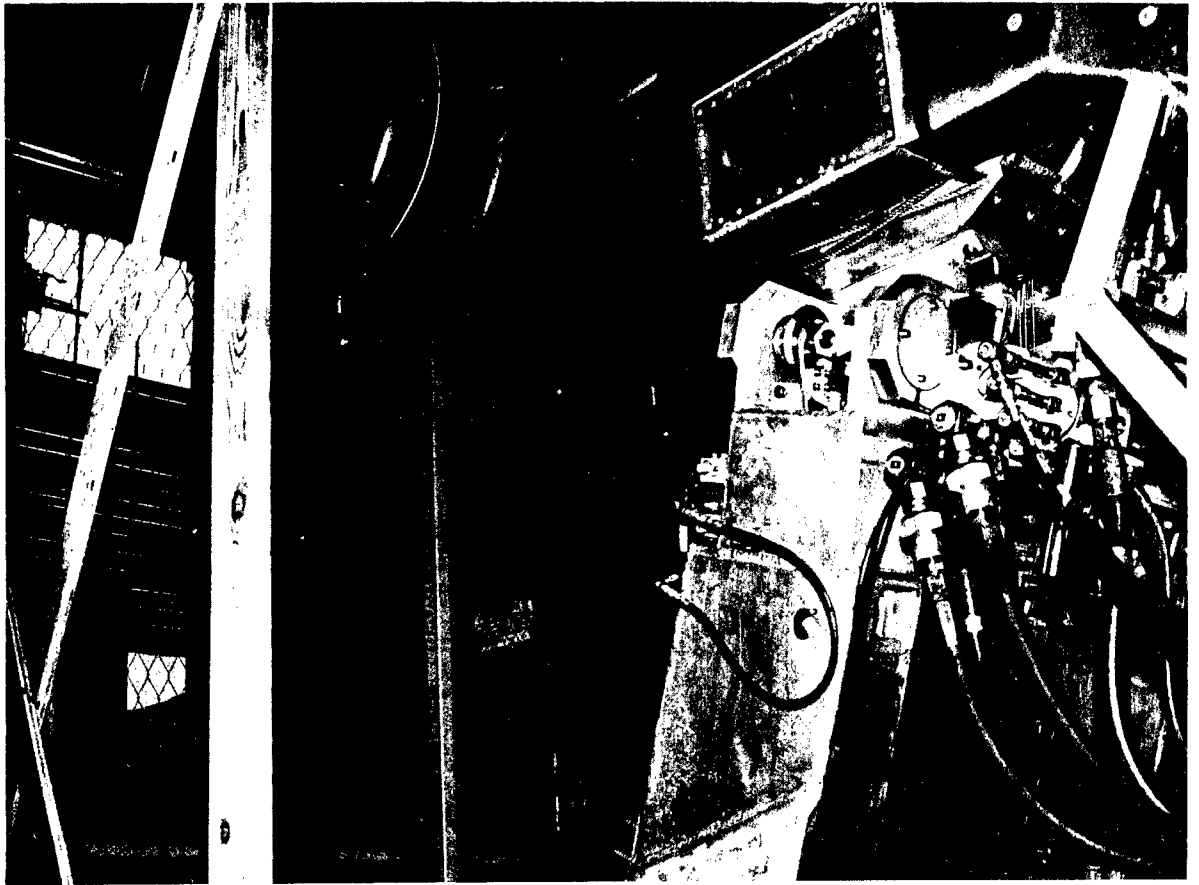


Figure 35 Aligning and Connecting the Pseudo Bomb to the Quadrupole

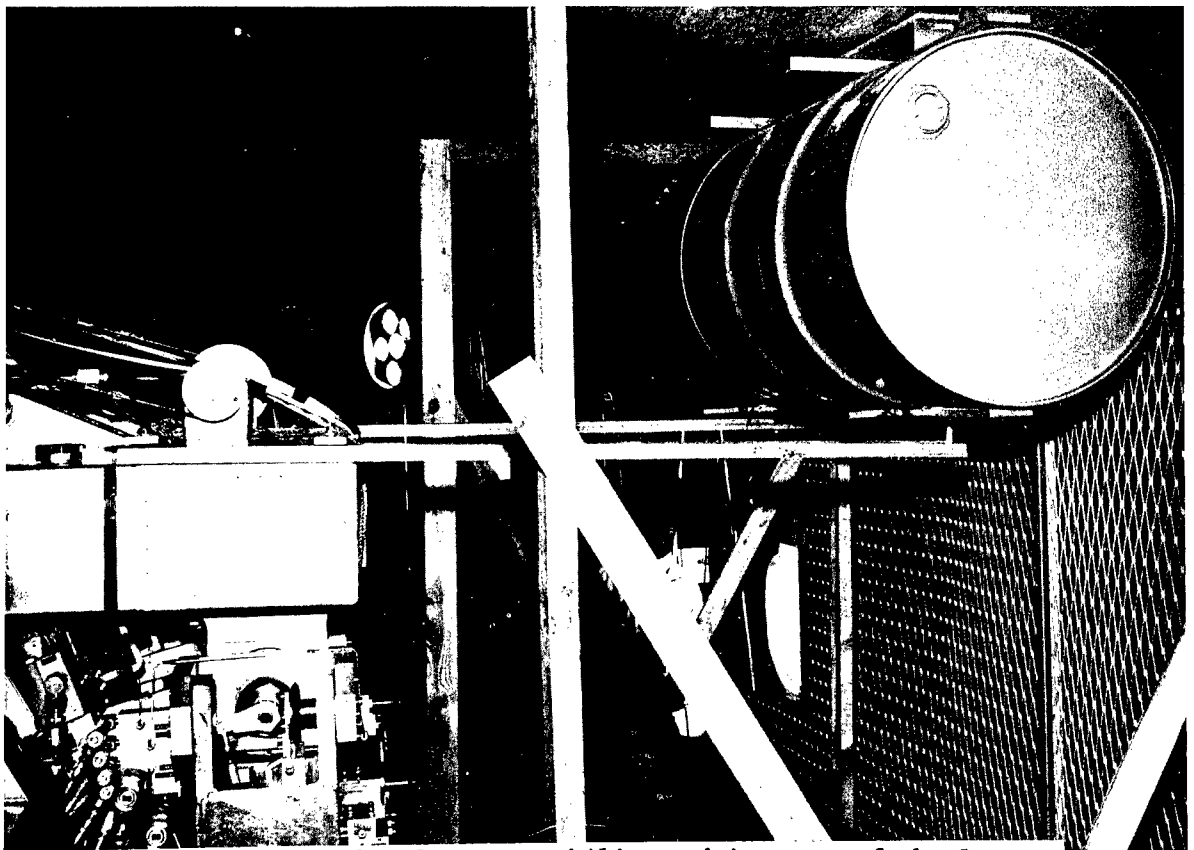


Figure 36 Example of Maneuverability and Accuracy of the System

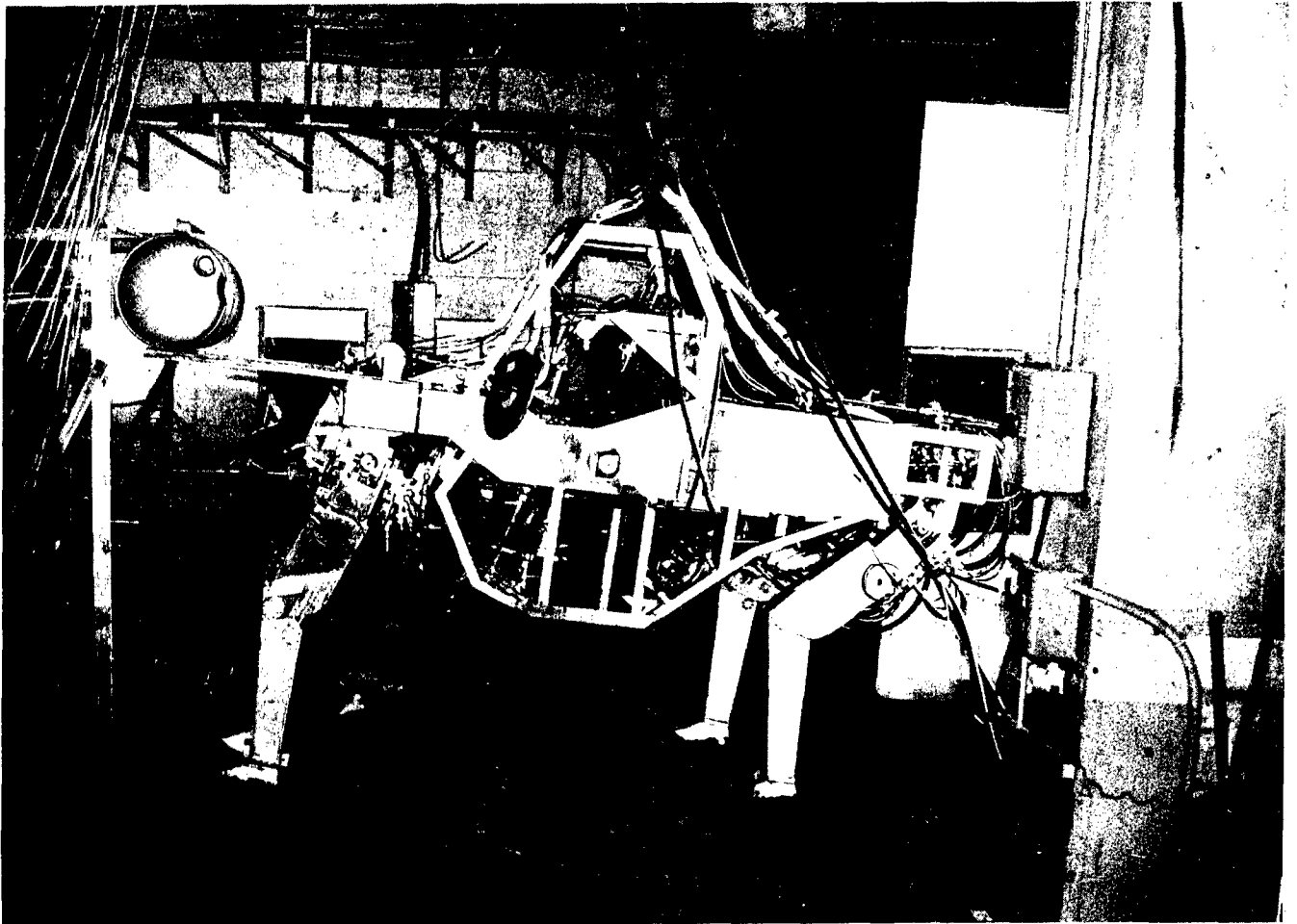


Figure 37 Loading Pseudo Bomb onto Simulated Aircraft Hanger Legs

To orient, position and affect discrete mechanical bomb-to-hanger lug connecting motions, accurate controllability of the six degrees of freedom in a space system was needed. This was realizable with the quadruped because of the ability to easily and simultaneously coordinate both the back and front.

It should be noted that all tests have been performed with the protective tether completely slack at all times.

#### Test Results

Trained operators were directed to operate the quadruped test bed without force feedback information reflected to the operator. This was done and, of course, position

feedback control was still in effect. The trained operator found it impossible to stand steadily; let alone walk or maneuver the vehicle. The machine merely shook in wild gyrations instead of operating smoothly. As a result of this test, it can be stated that force feedback is indispensable in complex position servo applications.

#### Potential Effects of Force Feedback Controls

Many improvements in performance have been accomplished by making small changes to the quadruped test bed. These small changes increased the results of performance in excess of the engineers' expectations. The future of this kind of man-machine control is viewed by the author with optimism. This experimental machine and the results of these experiments will provide valuable guidelines for design of new machines incorporating this control concept.

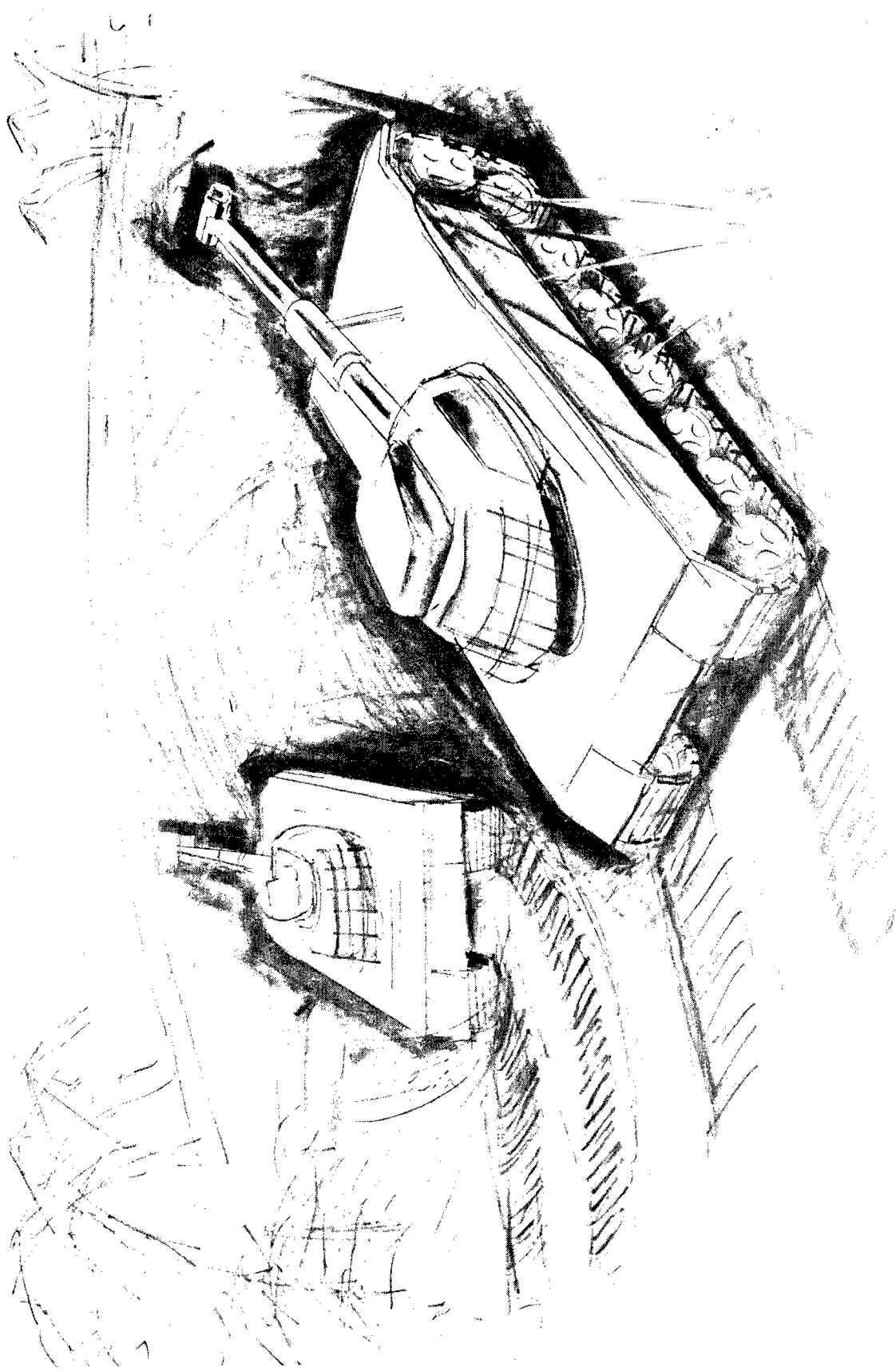
NEW MOBILITY CONCEPTSNew Design Possibilities Using Force Feedback Servo Technology

Somebody once asked Thomas A. Edison how he managed to continue through the years to be such a prolific inventor. He said that many ideas that he thought were great and worth working on turned out to be worthless, but most always, as a result of work done on each idea, two or three very worthwhile ideas were discovered. After reading a synopsis of his life, one cannot help but surmise that another important ingredient to his success formula was hard work. In other words, hard work on basically sound technical concepts is the "mother of invention!" However, sometimes it is hard to predict the birthplace. With this bit of philosophy in mind, the following concepts are presented.

The concepts are suggested to indicate the many approaches in designs that are possible with force feedback servomechanism technology. Some of them seem to be practical and others do not. However, even those concepts which turn out to be impractical may help trigger related ideas which are useful. It is believed that this technology promises to be the harbinger of new machines that will aid the soldier, alleviating some of his mobility problems. Control methods developed during quadruped test bed research program can be applied to different machine ideas to provide other possible applications of this control concept.

The illustration in Figure 38 shows two tanks climbing a muddy hill. The one on the left is driven by a less experienced driver who caused the left track to slip and dig in. The experienced driver on the right has learned to carefully balance the torque or traction in the two tracks. This fundamental point can be related to force feedback mechanism technology. The





## FORCE BALANCE TRACTION

Figure 38 Force Balance Traction

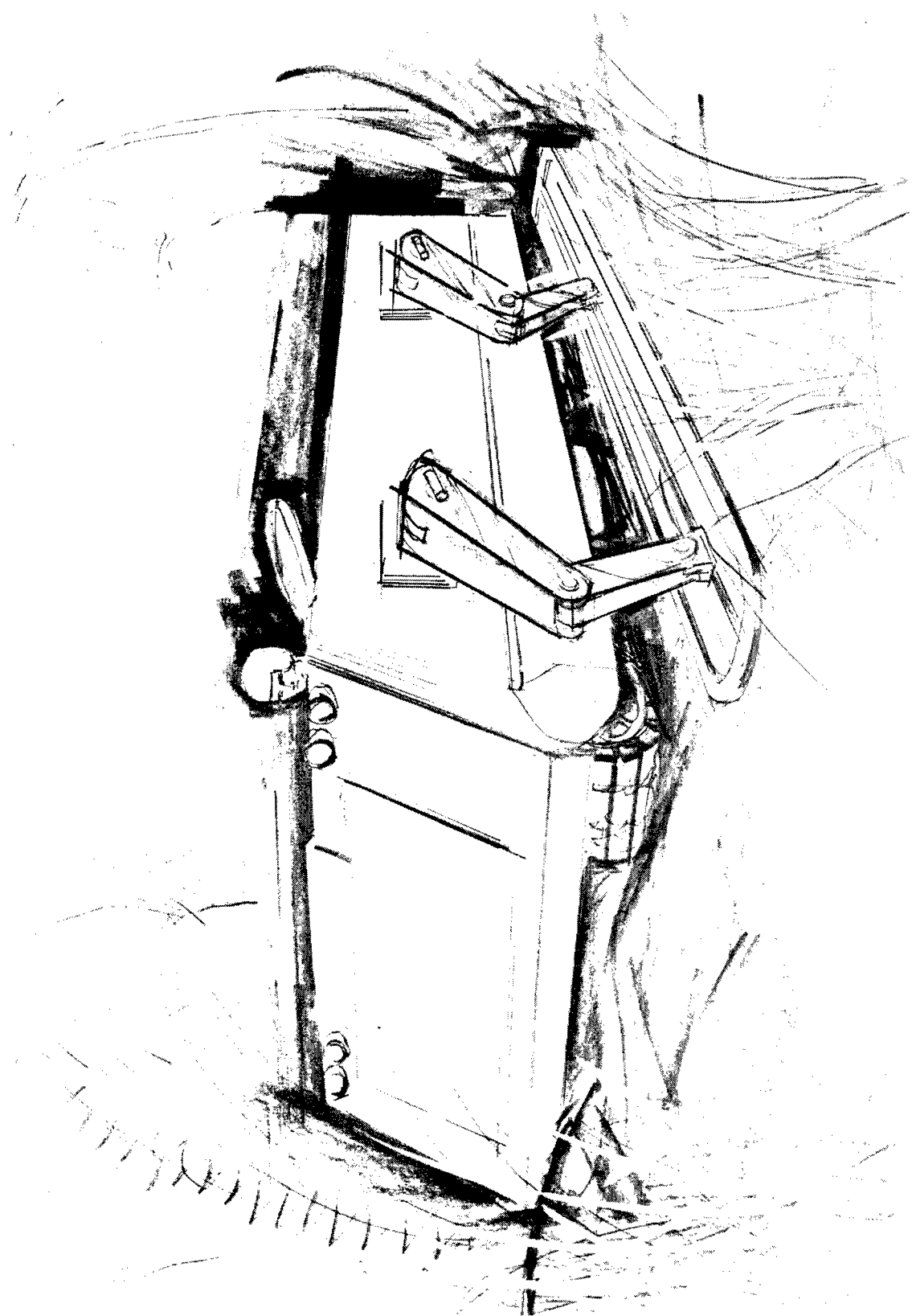
operator controls force levels in each of the two tracks. It seems very plausible that an operator control mechanism could be provided that would reflect track force information to the control handle. The mechanism could be designed to provide a preselected balance of forces with errors in this balance reflected to the operator. The reflected on balance could be compensated for by operator overriding control procedures. In this way the novice driver could become an expert with a minimum amount of training time.

#### Walking Aids for Stuck Track and Wheel Vehicles (See Figure 39).

Huge mine stripping shovels in Germany use modular walking legs to slowly waddle from place to place. This is practical because the machine is moved only a small distance each day. Using this same proven technique, one could attach four modular leg assemblies as aids to moving a vehicle out of a stalled situation. This leg assembly could be an emergency kit that is carried in a utility vehicle which travels with the caravan of vehicles. The vehicles could be designed to have standard arrangements for rapid attaching of the legs. The recovery man could control the leg system from a portable control station. Here again, characteristics similar to those of the quadruped test bed would make this concept workable.

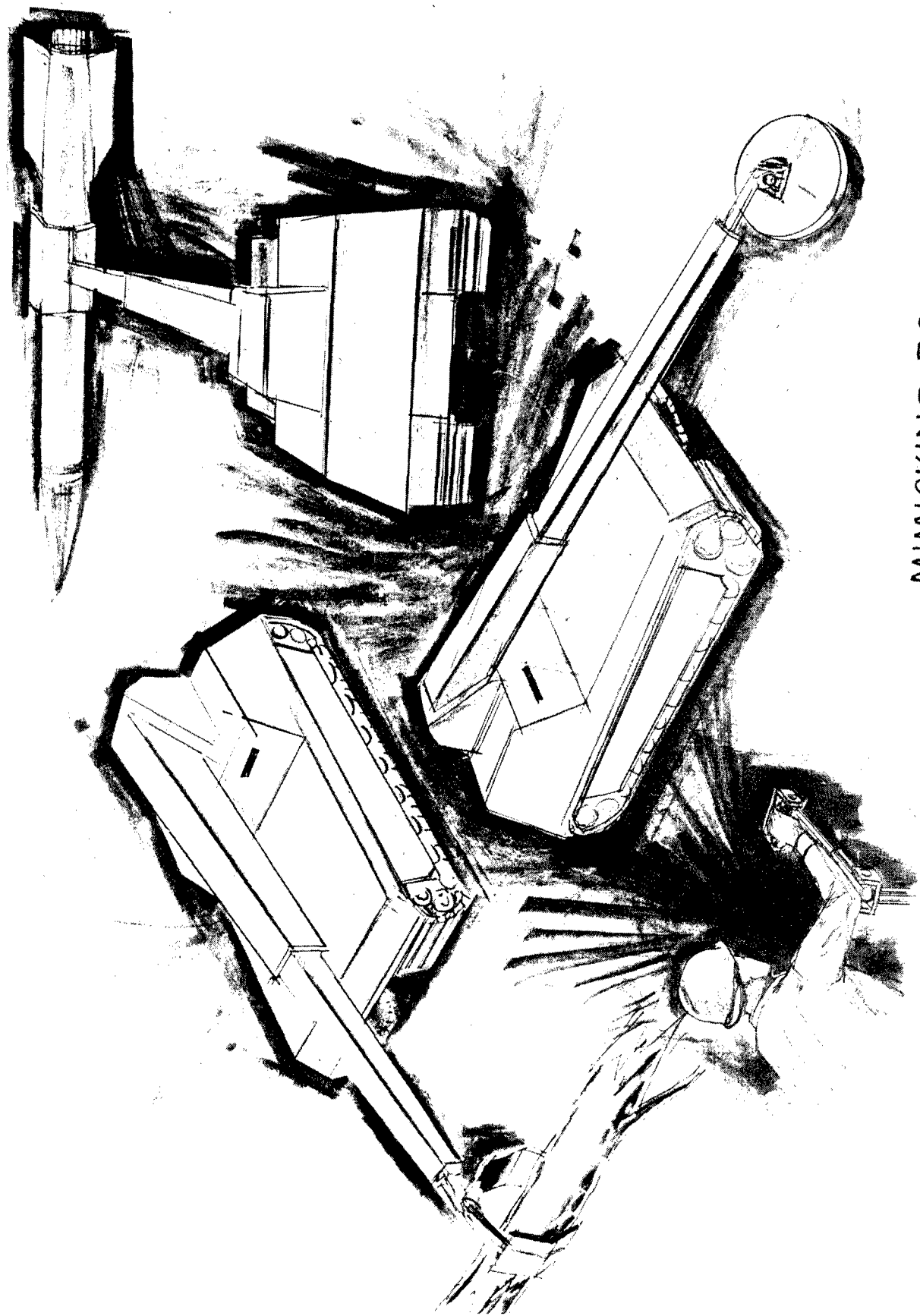
#### Self-Rescue Methods

The illustration in Figure 41 shows a tank with a pair of legs that can lift the front end out. Of course, it is understood that this leg system must be very massive and strong. If such an approach were to be proved practical, the best design technique might include straight inline telescoping legs and be mounted directly in front and under the vehicle. The leg system would probably have a very large walking plate or shoe that would provide the necessary low bearing pressure. Shown at the back end of the tank is a second pair of legs which have a blade similar to the bulldozer blade connected to them. These could be used in unison to



## LEG RETRIEVER MODULES

Figure 39 Leg Retriever Modules



## MIMICKING BOOM

Figure 40 Cobra Vehicle Mimic Control

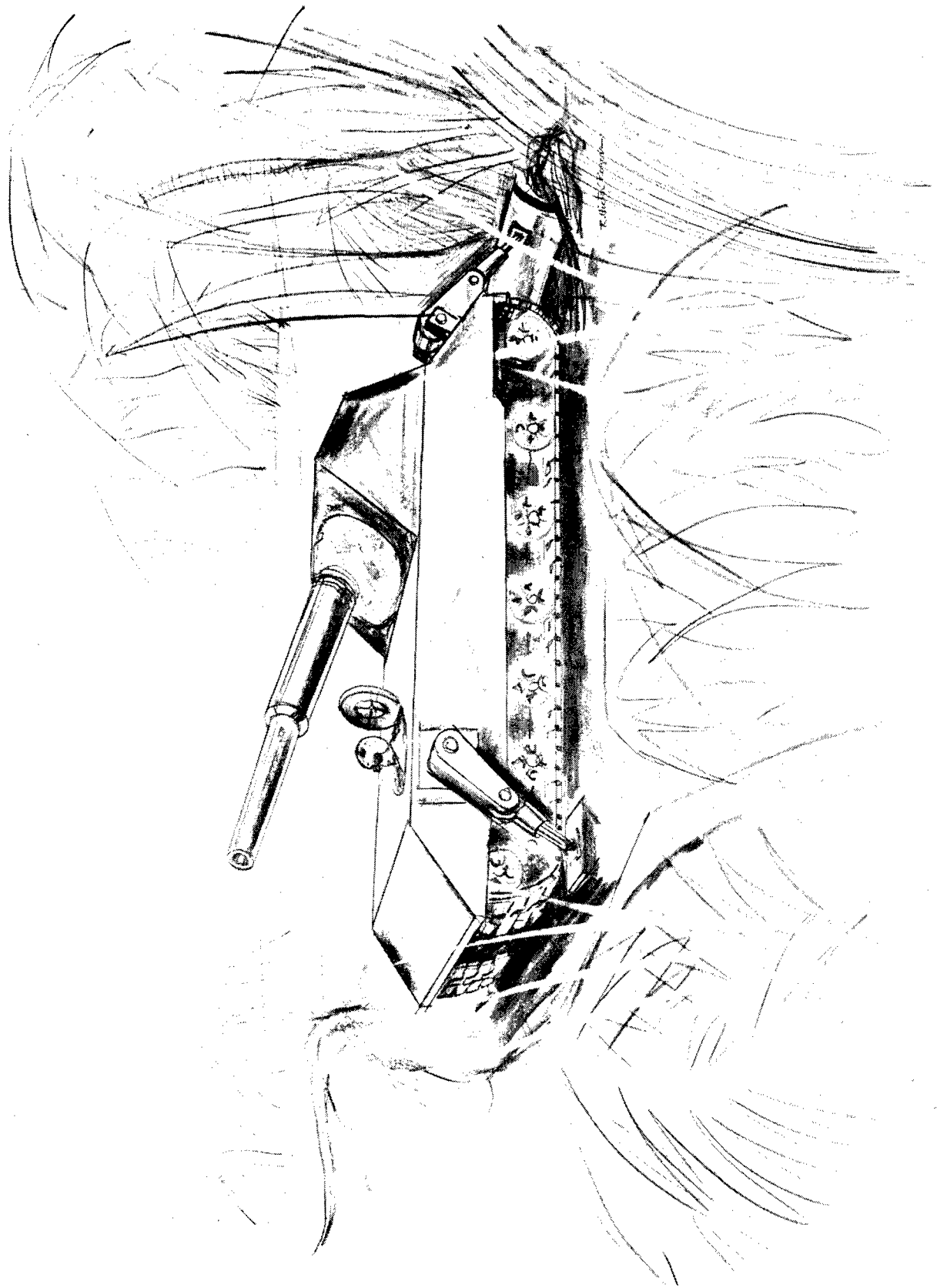


Figure 41: Self Rescue Methods

provide the thrust in combination with the front end lift required to jack the vehicle out of its stuck position. Again, this arrangement can be considered one where the leg systems are modular and to be attached to standard connecting points on the vehicle for the extraction process only. They would be carried in a special rescue vehicle and be used as rescue equipment for all vehicles. This "lift push" leg system could be reversed on the vehicle so that jacking in a reverse direction would also be possible.

### Versatile Working Leg

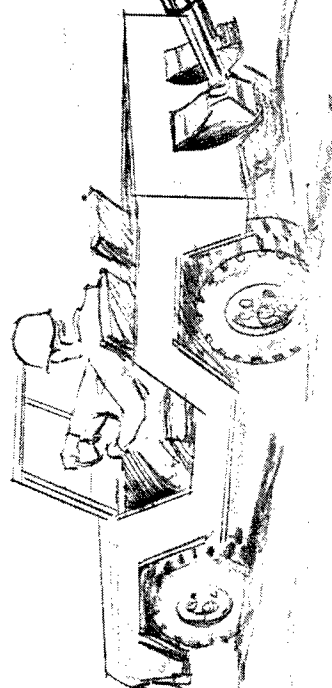
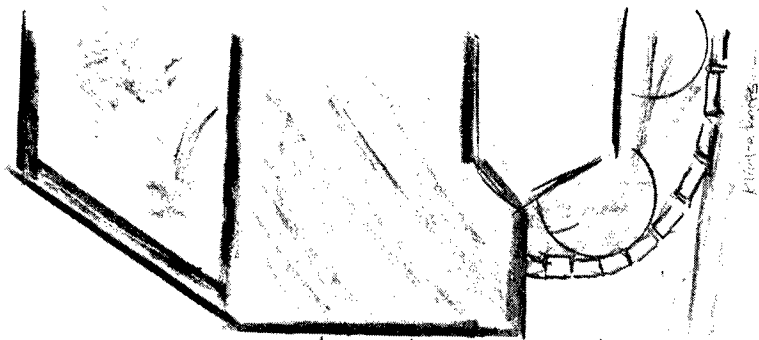
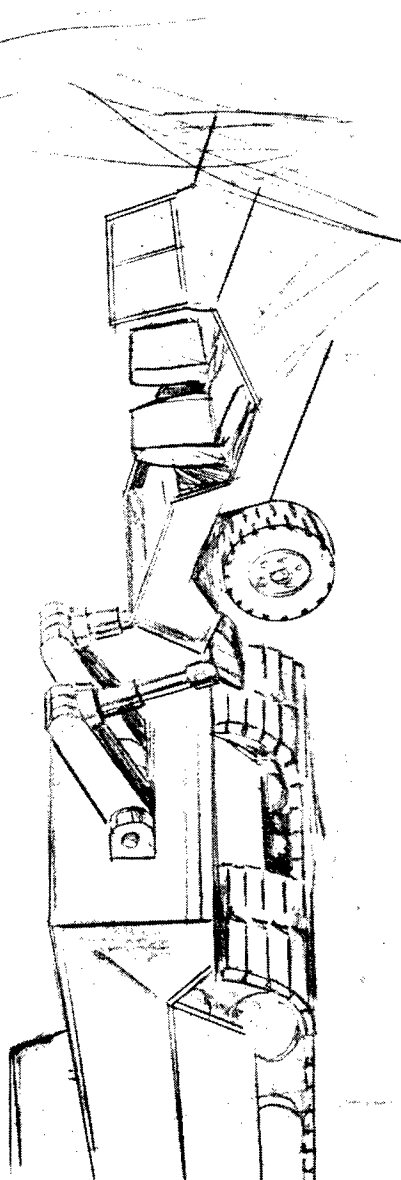
Figure 42 illustrates how the articulating (or telescoping) leg can be used for a variety of operations where the versatility was made possible with the mimicking operator control. It would be very simple for either two legs (connected with a push-a-blade) or a single leg to gently pick up the rear end of a vehicle such as a jeep and shove it out of a stuck position. Furthermore, the leg or pair of legs can be used as a compliant coupling between two vehicles where one is pushing the other. The dexterity of the leg would make it easy for the operator to select an appropriately rugged spot for contact of the pushing leg. The irregular motions between the two vehicles would not cause rubbing or scraping between the two because the connecting leg system would comply to the generated forces.

The leg acts as a subtle, flexible coupling link between the two vehicles. Forces between the two vehicles would be minimized and smooth transition of forces between them would be possible.

### Vehicle Leveler

With attachable legs or jacks, it is possible to park a vehicle in extreme terrain conditions where normally the orientation of the vehicle would prevent adequate fire control flexibility (see Figure 43). The idea is to rapidly orient the vehicle and then retract the jacking legs quickly so that the vehicle could easily and quickly scoot to a new site.

FORCE CONTROL-PICK



FORCE CONTROL-PUSH

Figure 42 Working Legs

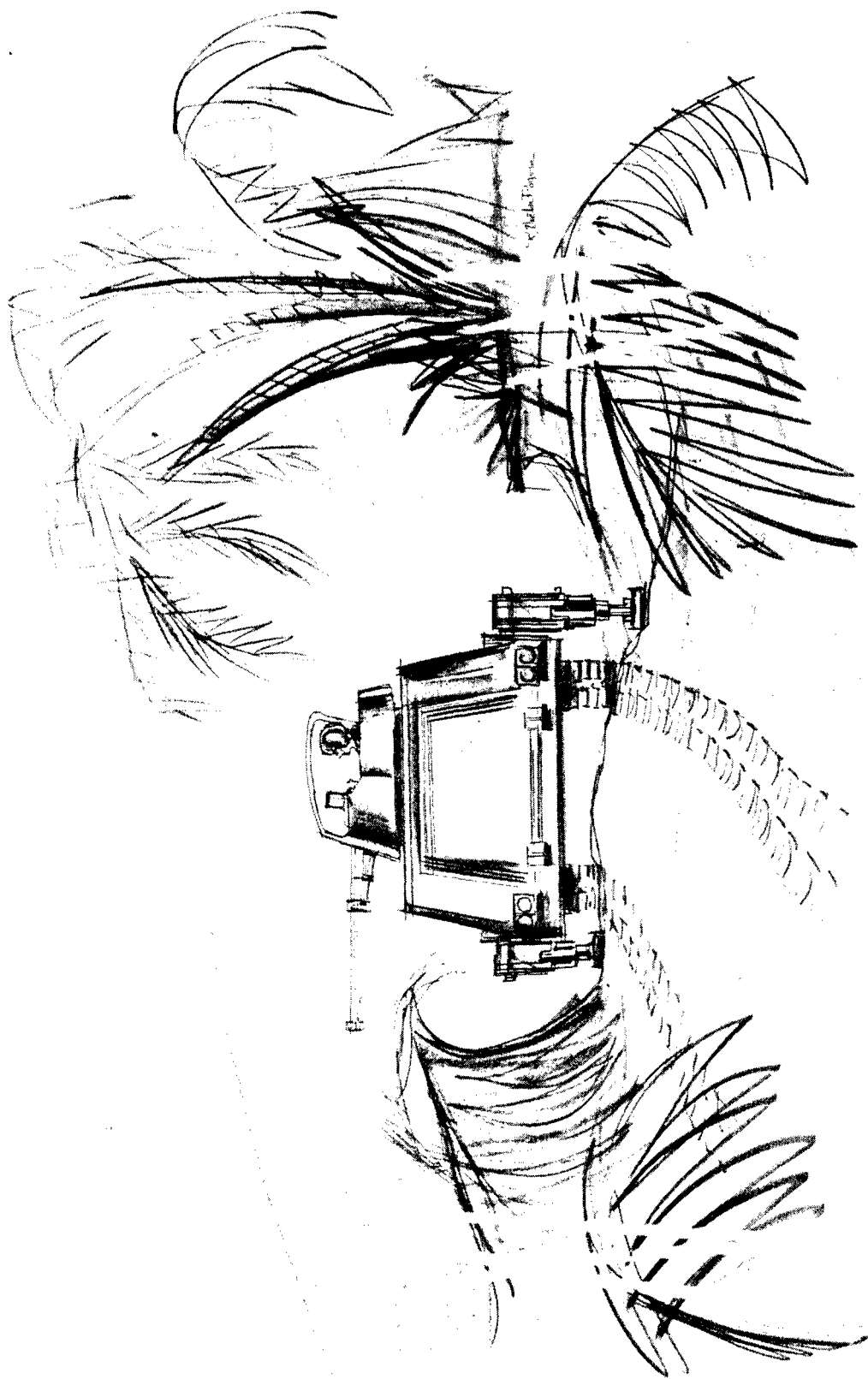


Figure 43: Vehicle Leveler



#### Cable Tow Winch - Force Controlled (Figure 44)

When winding vehicles, the uncontrolled forces generated in towing have often inadvertently damaged the vehicle. It has been suggested that a force-controlled winch system be developed. This can be done and the operator can be supplied with a simple lever that controls the amount of force generated. It would reflect to the operator a proportion of the force generated by the cable. This force capability would provide any untrained GI the capability to tow gently with controlled force. Force sensitive servos respond to force information much faster and more accurately than the usual position control servos. Furthermore, with the servos reflecting force to the operator, the operator responds very quickly where reaction depends only on force sensing with spatial correspondence. The operator's reaction time is not dependent on his mental awareness or the time required to reason out control logic. His speed of response is limited only by his neuromuscular reflexes. A little insight can be gained by recalling the familiar problem of towing one car with the other and attempting to prevent jerking forces between the two vehicles.

#### Mimicking Boom Control (Figure 45)

Spatial correspondence and force feedback mechanisms are considered tools that provide a man with a means to augment his capability without the loss of human alacrity and sensing capabilities. A man-operated mine detector is necessarily small because of the human physical limitations in manipulating the device. With force feedback control, it is possible that the man can cause a very large mine detector to perform as well as a small one operated directly. With the mimic control, the operator would find it easy to sweep the irregular contours of the terrain in front of him with accuracy and speed. His operating station would be within the vehicle protected from enemy action and it would be very possible that the boom could be provided the necessary properties allowing it to recoil from an explosion with a minimum of damage to the boom. As the illustration

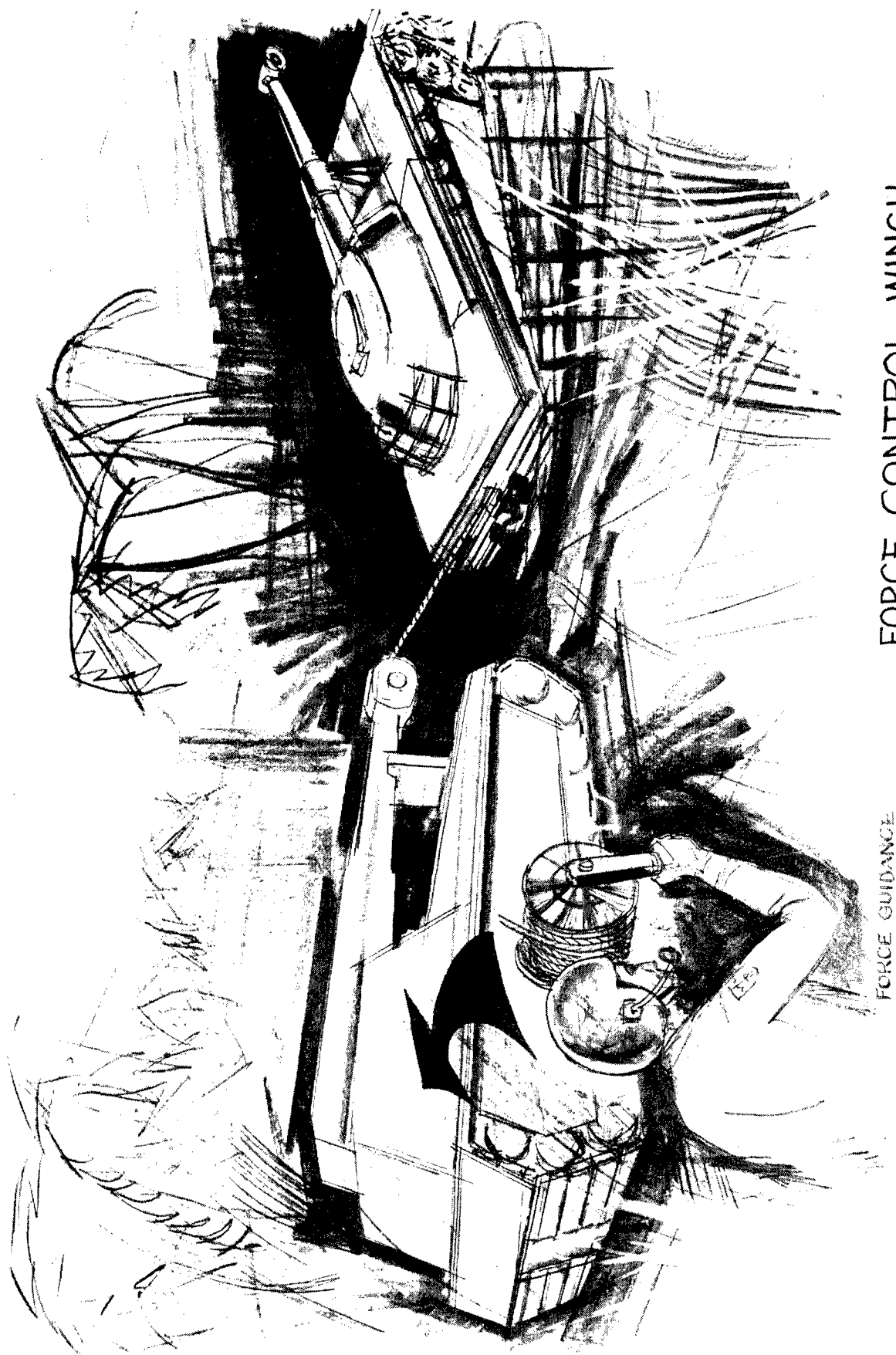


Figure 44: Force Controlled Winch

indicates, the boom would have some of the versatilities of the man and could be adapted for many other uses such as missile assembly work, loading and launching of missiles and clearing debris off a roadway.

Through the development of manipulators to handle nuclear materials in hot shop laboratories, this basic concept has been proven practical. However, it remains to be proven that this technology can be applied to larger booms such as illustrated here and be made practical.

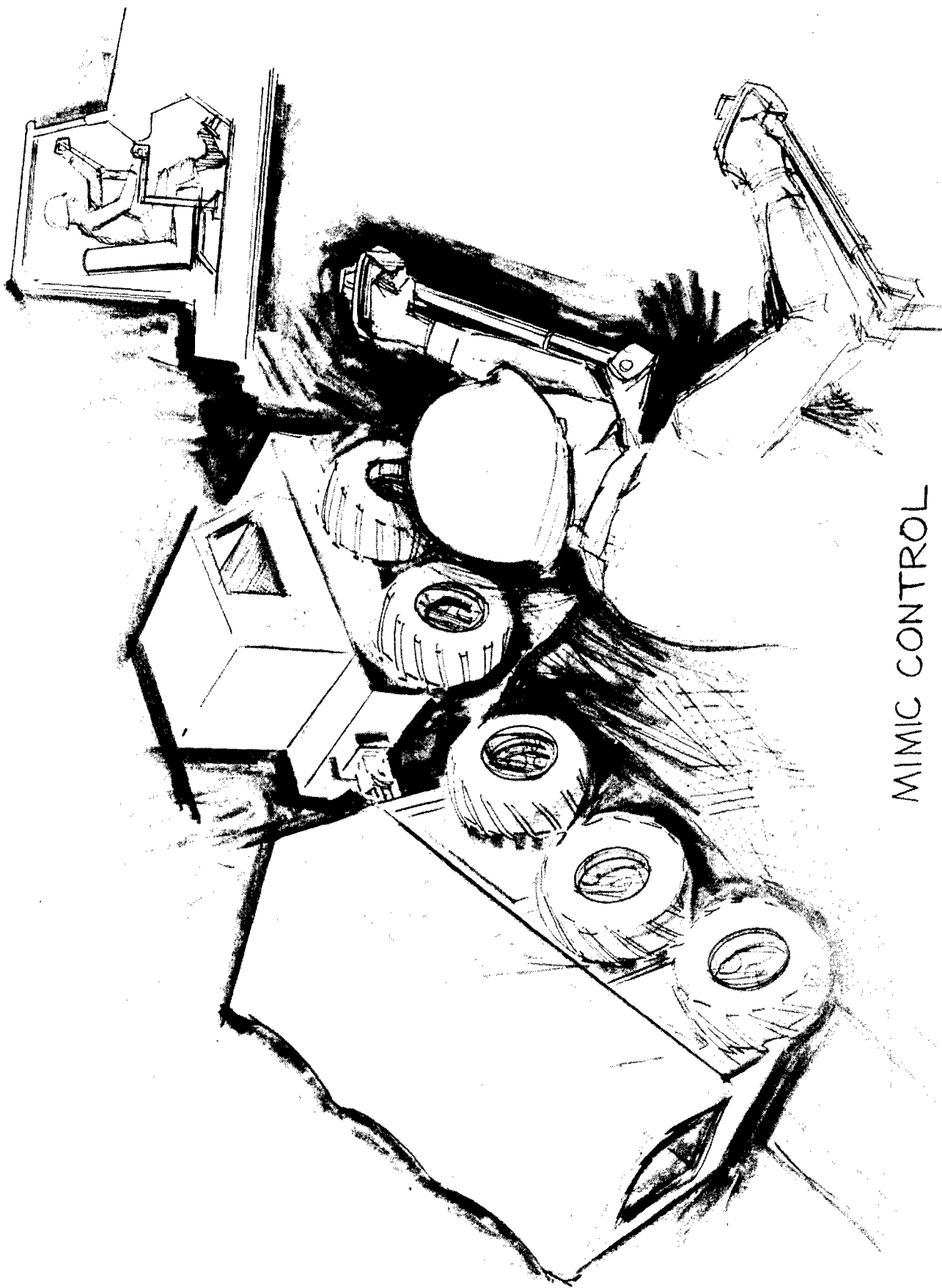
### Missile Launcher

Figure 46 shows an illustration of a boom that could be used to provide a raised missile launching platform. The raised platform would allow the vehicle to be located in a protective situation, such as shown. This concept can be identified as an aid to mobility because this boom device would provide a larger choice of favorable launching sites.

### Articulating Boom (Figure 47)

Material handling is a severe Army problem and seems to be getting worse. Some aspects of material handling are directly related to the problems of mobility. Mobility means transfer of material as well as people from one place to the other. As an example, commercial companies who are in the business of moving material are very concerned with the time required to load and unload the material. Truckers of bricks, as an example, have solved this mobility economics problem by using permanently mounted booms on the truck, to load and unload palletized bricks. Logging operators and many others do the same thing.

It has been the experience of people using these articulating booms that it is difficult to train and keep proficient operators. Logging people have shown strong interest in exploring the possibility of using spatial correspondence with force feedback control mechanisms to circumvent this problem. This approach would solve the problem and also increase the speed of



## MIMIC CONTROL

Figure 45: Mimicking Boom Control

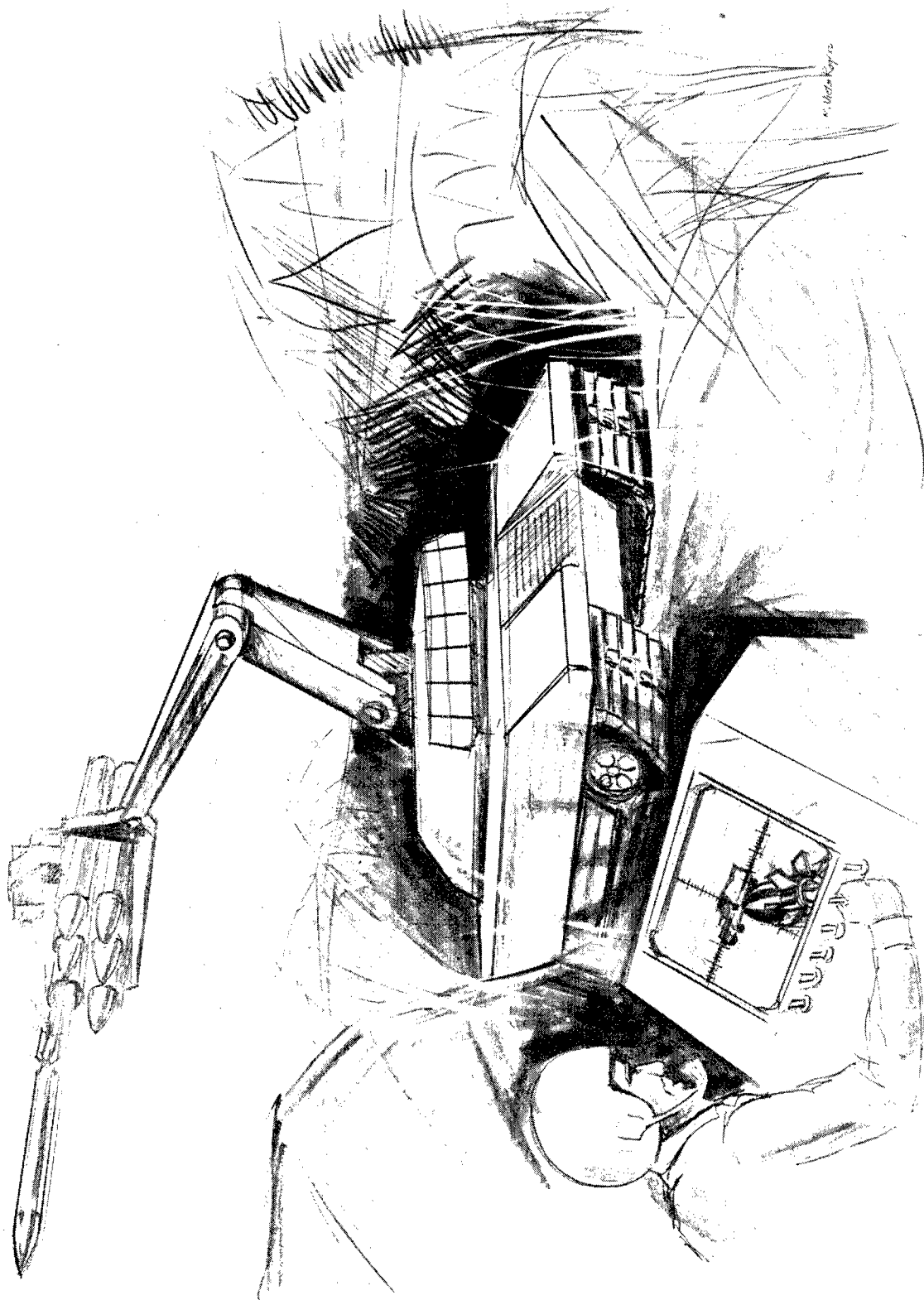


Figure 46: Missile Launcher

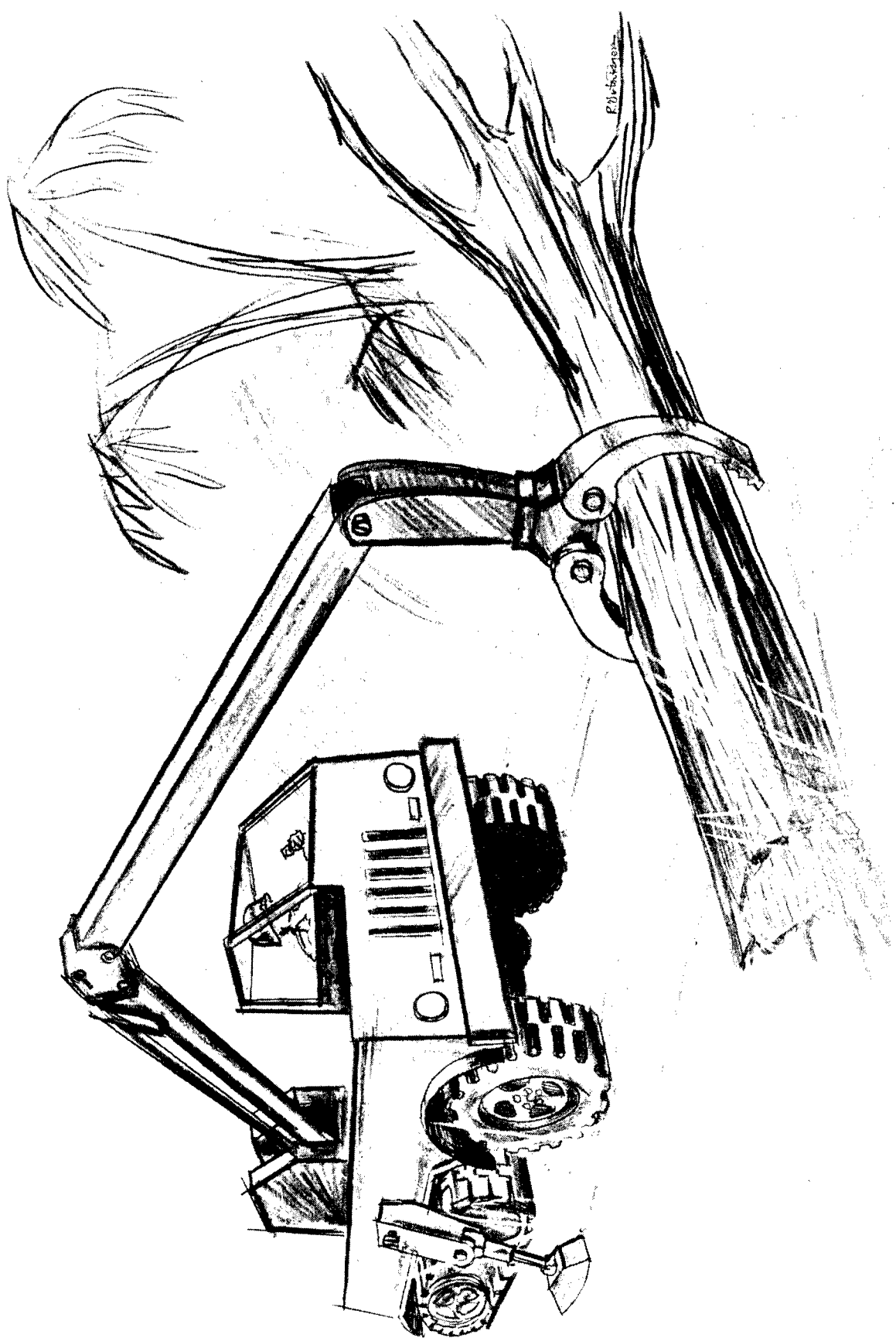


Figure 47: Articulating Boom

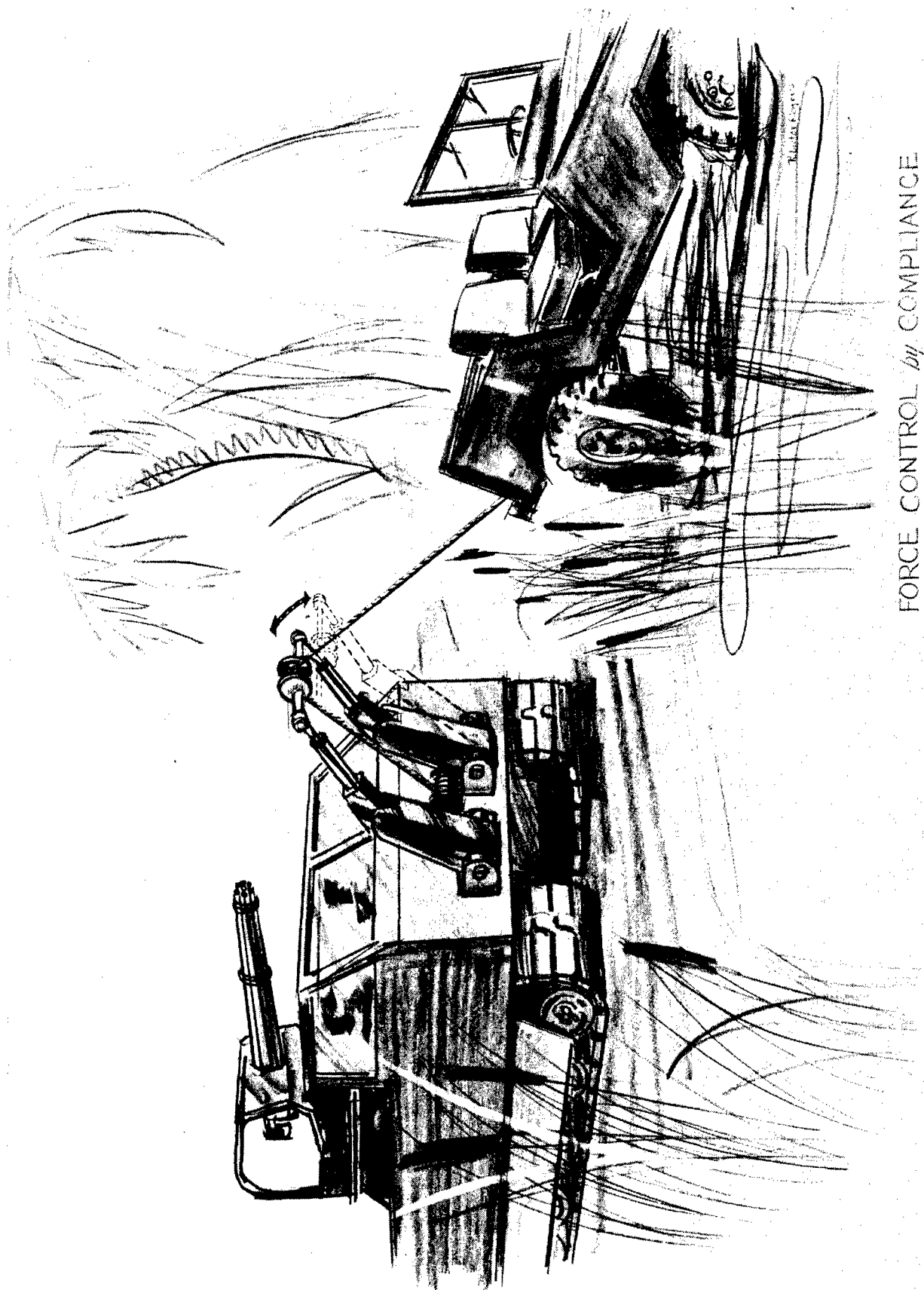
the operation. The Gradall boom used for construction work is a good example of where this control concept would work very well. The reason is that the machine has five basic motions similar to the human arm. The master-slave concept could be easily adapted to this machine. The articulating boom illustrated in Figure 47 is suggested as a means of providing a general utility device.

### Two Cable Force Control and Indicator

The illustration in Figure 48 shows a boom which could be a variation of other articulating legs or booms. This device could be used to control the force level in the cable and also indicate this force level to the operator. A standard winch system could be used where the force feedback boom would provide force information to the operator and reaction time that would let him control the winch forces. Paper mills use this concept to control the tension in the miles of paper that are continuously fed around a multiplicity of rollers. A simple, inexpensive model of this concept could be built for test and evaluation. As a matter of fact, one of the legs of the quadruped test bed could be used to evaluate this concept.

### Wheels Used as Legs

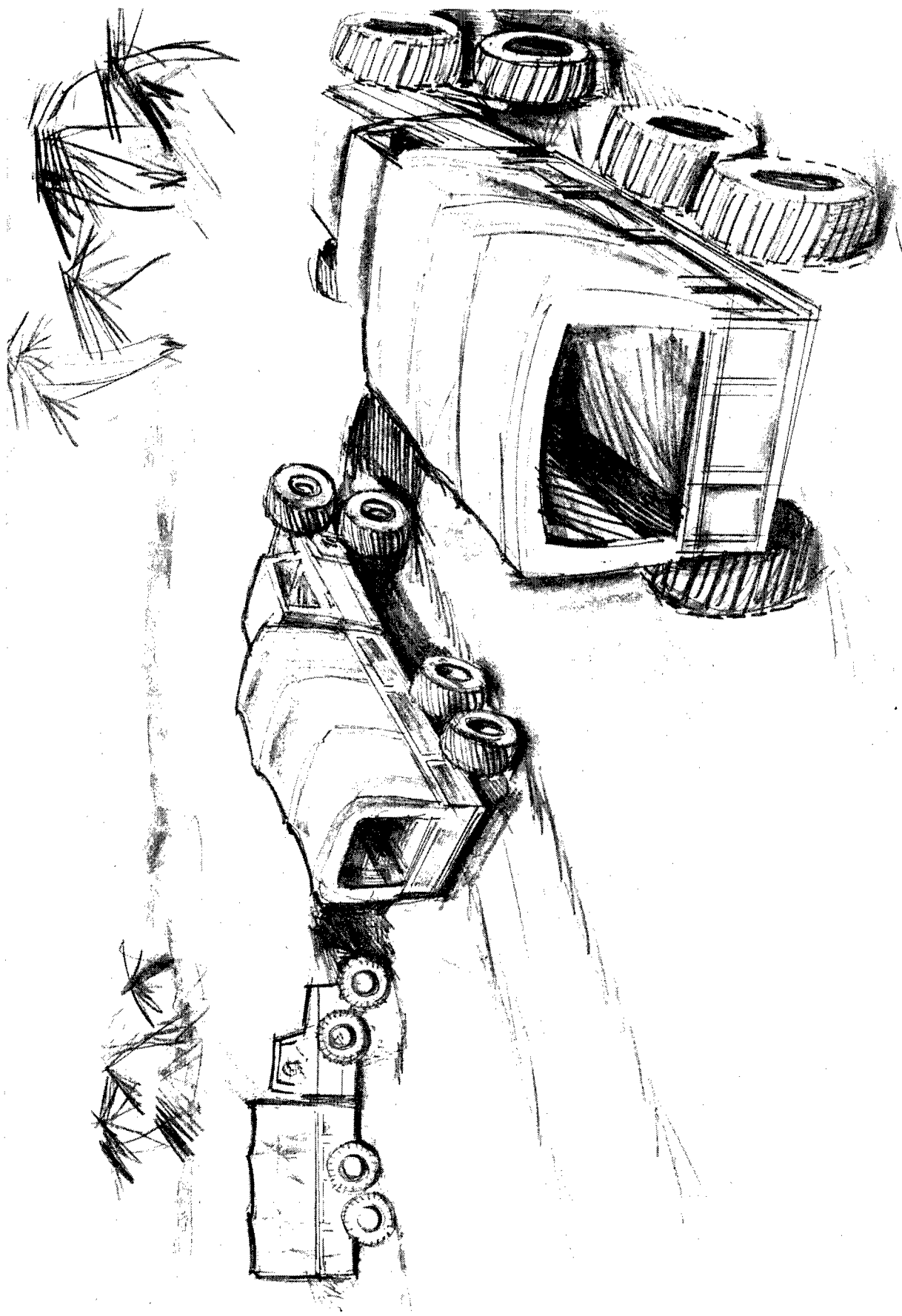
It is understood that many ideas have been presented that involve a combination of wheel actions such as rotation and orbiting. The idea shown in Figure 49 is different in that an immobilized wheel experiencing slipping and bulldozing will transfer its action from wheel rotate to straight-line rearward motion. The translation motion is not an orbiting or circular action. This concept is a direct outgrowth of the thinking involved in developing the walking vehicle. Although the stepping device involves wheels, it is truly a stepping device. The translation motion and the stepover motion of the second wheel act as a bipedal motion of one leg stepping over the other. The chassis of the vehicle is promoted forward just as the human body is through the pelvic action. It can be thought of as being similar to pole vaulting, one over the other. The concept does not



FORCE CONTROL *by* COMPLIANCE

Figure 48: Boom for Cable Force Control



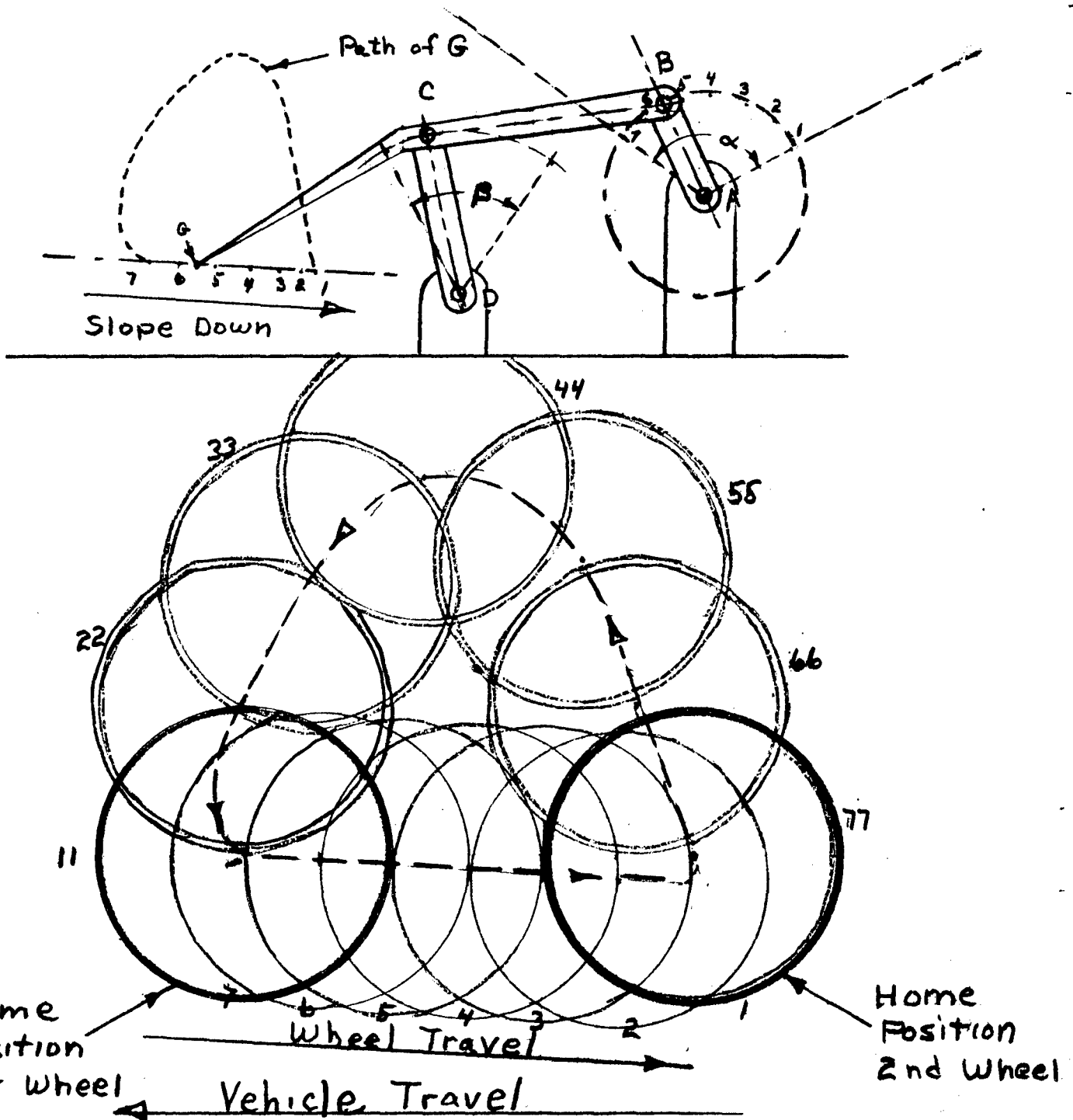


## WHEEL WALKER

Figure 49: Wheel Walker

Figure 50: Wheel Walker Kinematic.

## Two Wheel Rotate-Step Combination



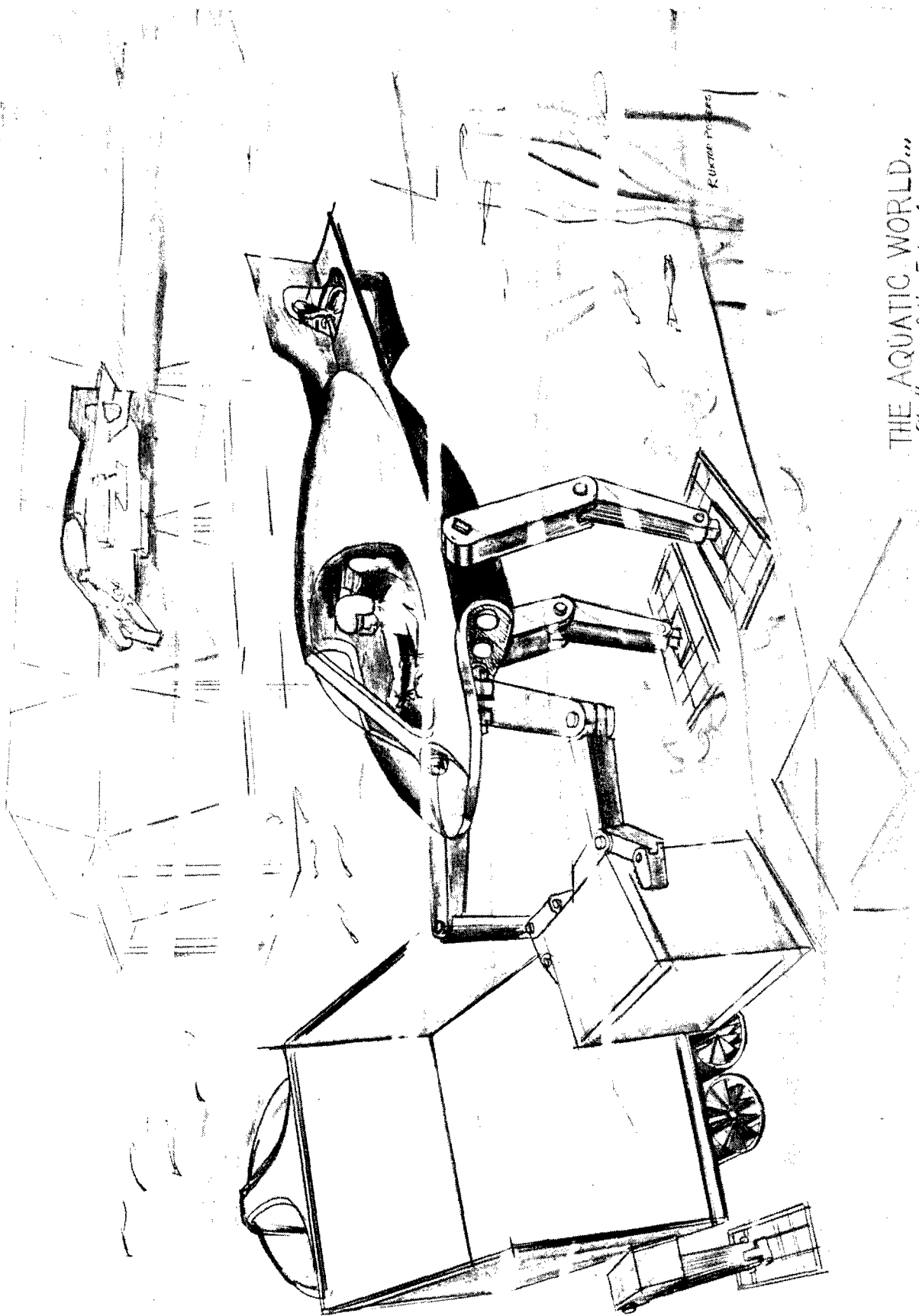
depend on terrain shear strength in the lateral direction. All that is required to make this concept work, in terrain properties, is adequate load bearing capacity.

Figure 50 shows a schematic diagram of a linkage concept that could provide this translation and stepping motion for this dual wheel system. In this diagram, a multiplicity of circles represent the proposed action of the two wheels. The first wheel is shown in the forward position. It is proposed that encountered frontal resistance or wheel slippage will cause the wheel to travel rearward and slightly down. At the same time, the stepping action occurs with the second wheel. The relative positions of the two wheels are indicated by single and double numerical connotations. As an example, position 7 of the first wheel corresponds to position 77 of the second wheel. This diagram indicates start of motion with the highest digit first, so that motion of the first wheel is shown to start at position 7 and the motion of the second wheel starts from position 77 (and at the same time as the first wheel starts). Home positions are shown as number 1 and 11. Of course, this two wheel system would require two sets of the four-bar linkage system shown. The two pair of four-bar linkages would be interconnected to operate as complementary pairs with the motion of one four bar linkage depending on the other. A differential transmission would provide transition from wheel rotary motion to stepping action. The idea of the slight slope of the straight line motion is to provide automatic preference of wheel rotary action compared to the stepping motion.

There are two key principles involved. One is the principle of stepping action and the second is the use of force reaction on the wheel to provide selectivity of the wheel rotary motion for the translate and step motion. It is beyond the scope of this report to analyze and design the complete system such as suggested by this concept. However, the concept is outlined and it is suggested that at least some more thought be given to this idea to determine feasibility and practicability.

#### Underwater Army Bases and Depot (See Figure 51)

Recent marine biology and ocean engineering work have resulted in some startling underwater activity concepts



THE AQUATIC WORLD...  
*Challenge of the Future!*

Figure 51: Under Sea Mobility

and systems designs that promise to pave the way to a profitable exploitation of untapped water resources. It is not difficult to argue that before this decade has passed the Army, as well as the Navy, will be involved in exploiting and protecting our underwater territory.

Already, large oil companies are competing for underwater rights for oil well operations. The United States government is the guardian of this territory and has the specific operational guidelines. Petroleum industries are currently designing huge and complex underwater oil mining operations. The author predicts that some day in the near future they will operate their own underwater stations. There are obvious advantages to this foray into our underwater territory.

The petroleum industries have found that to operate these underwater complexes they need transportation and mobility. They have design vehicles that travel from the surface down to the site and are able to do work by means of underwater manipulators. It follows that a necessary and valuable tool for underwater work will be unusual vehicles that can provide the ability for man to work remotely as he would on earth directly. The illustration in Figure 51 of this unusual underwater vehicle is a concept that might not ever be realized. However, it is predicted that the elements of this concept, the legs, and the manipulator arms, and the man's ability to operate the vehicle from within, are concepts that will be used to provide the kind of functions illustrated.

#### Standard Modular Force Feedback Components for a Variety of Applications

Shown in Figure 52 is a drawing of a modular unit. It is shown with a configuration that can be easily mounted in a variety of orientations and many locations on different vehicles. With this standard component design approach, the device can be carried as spare

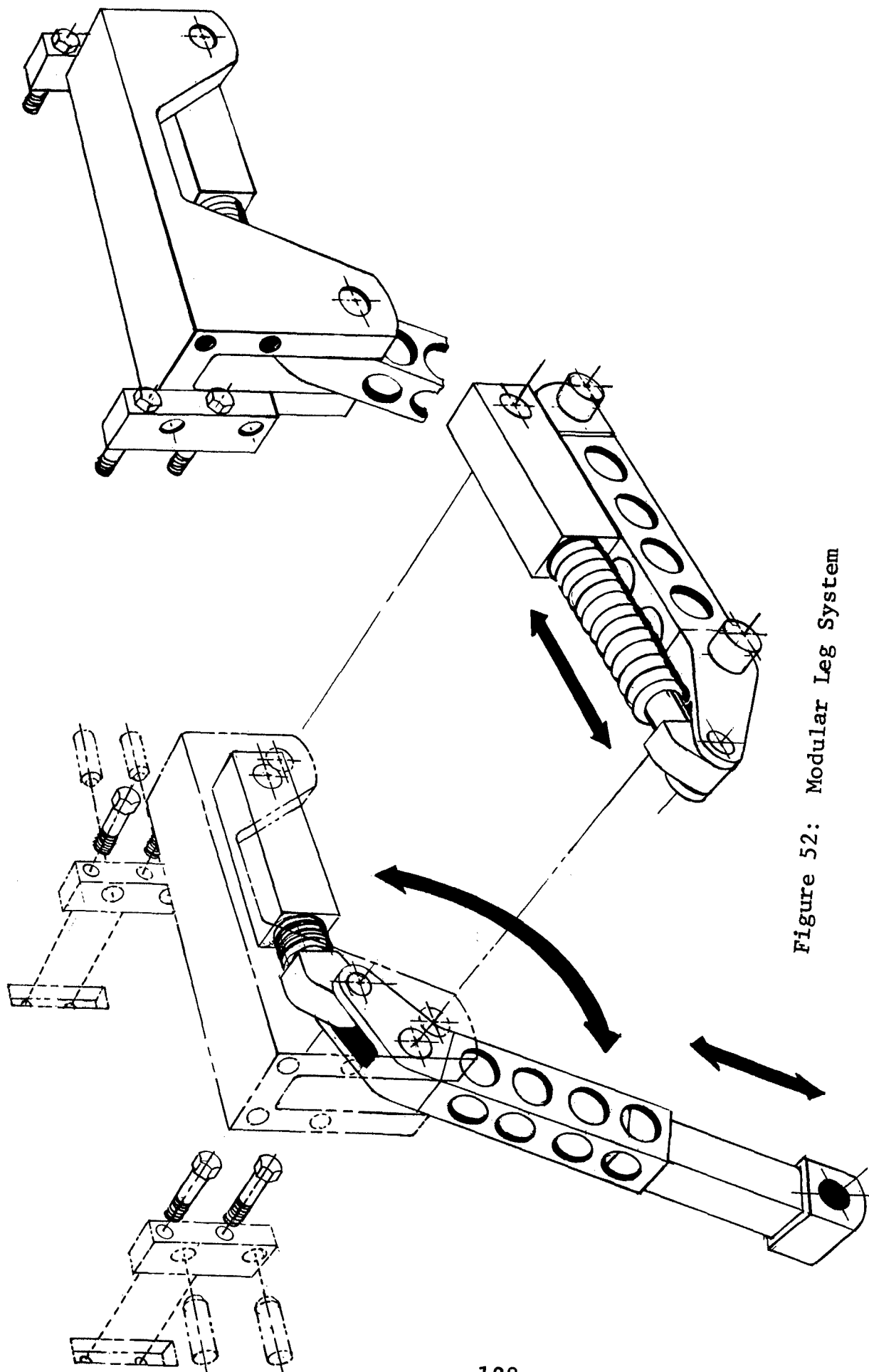
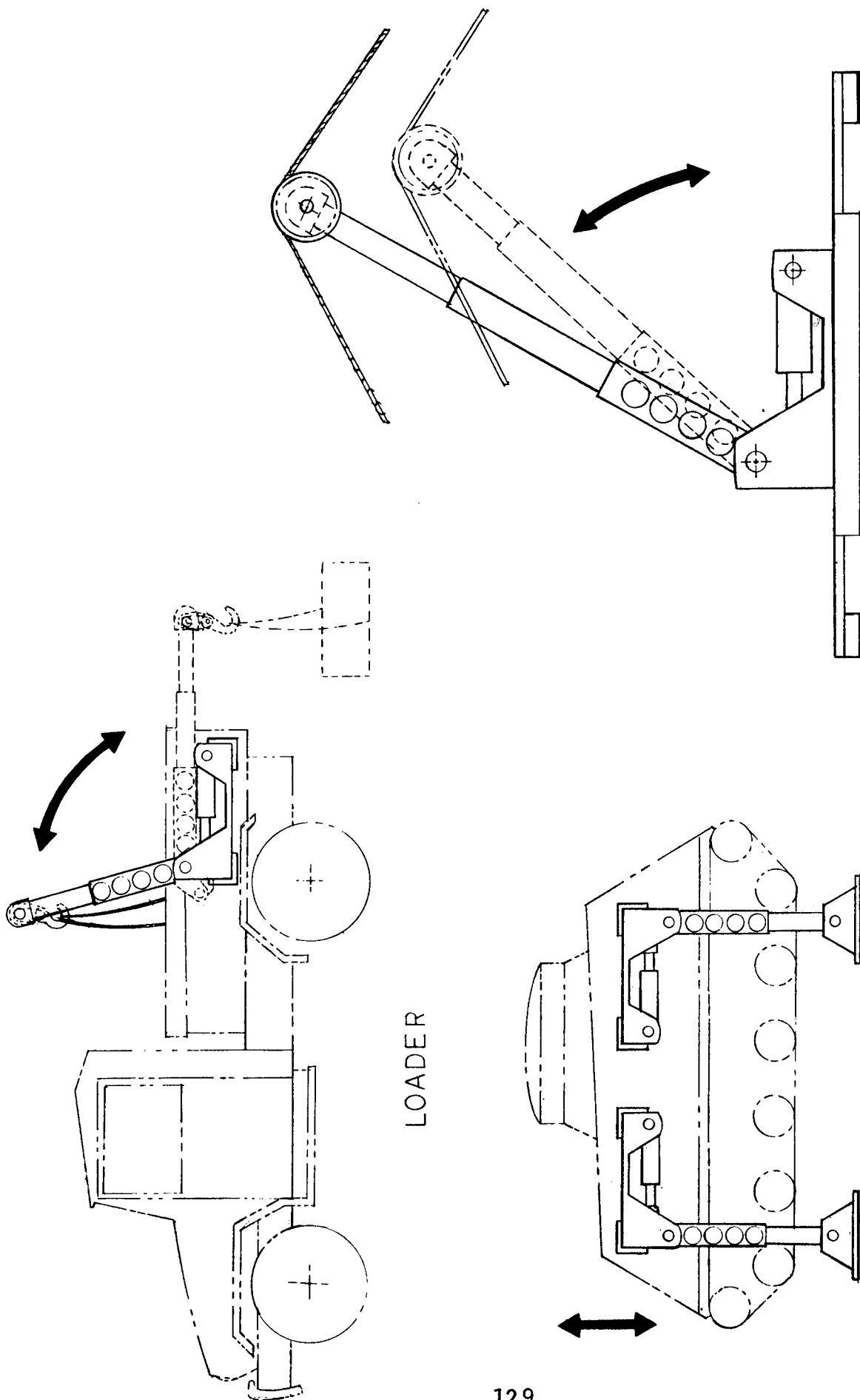


Figure 52: Modular Leg System

*BASIC ARTICULATING ARM  
(STANDARD MODULAR UNITS)*

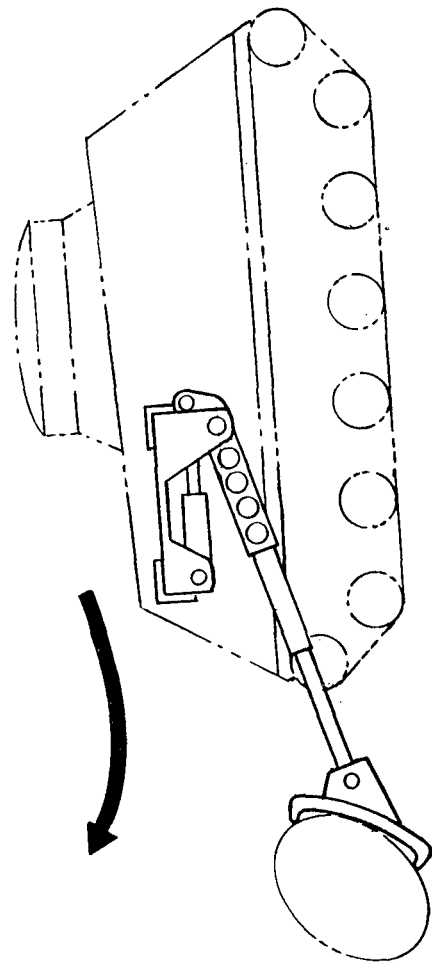
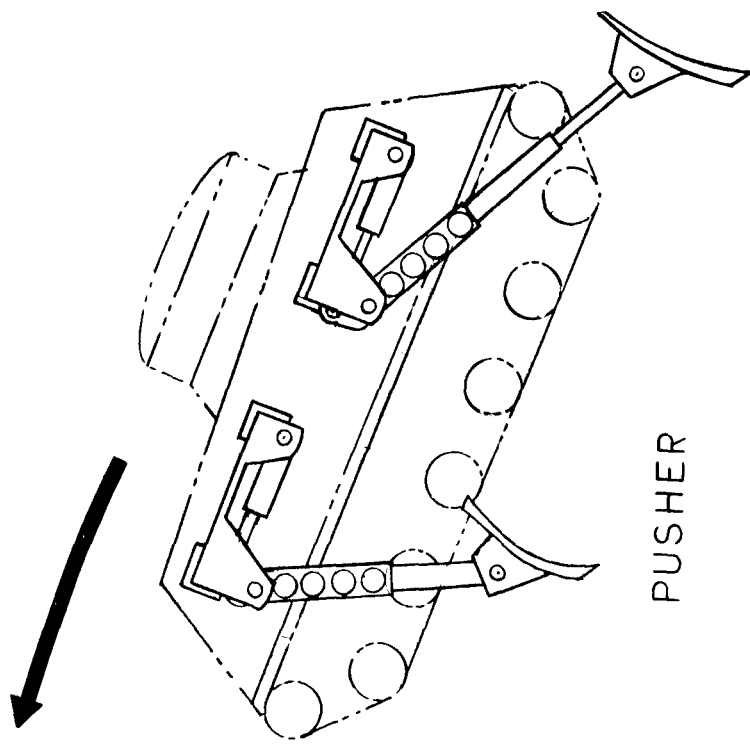
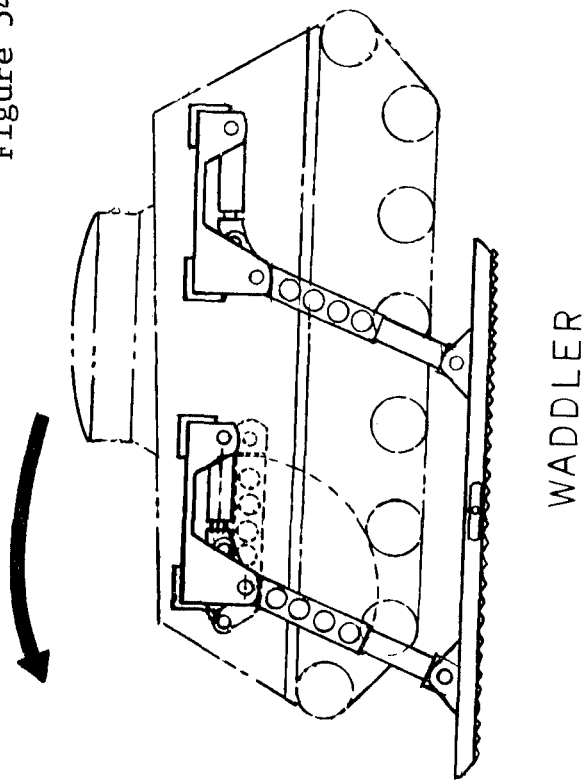


SERVICE JACKS

RIGGING TOOL

Figure 53: Modular Legs for Walking

Figure 54: Modular Legs for Auxiliary Work





equipment in one vehicle and serve all vehicles in the caravan. The master control unit for this component would be a standard modular unit and part of this standby equipment. Figures 53 and 54 show possible applications for this standard modular unit.

FORCE FEEDBACK-POSITIONAL SERVOMECHANISM  
ANALYSIS AND DESIGN CRITERIA

Many machines are designed to respond to a man's physical actions. It follows that these machines could be improved if the controls were designed so that there is a reciprocity of force and position information between man and the machine. Examples of such man-machine servos designed with force and position feedback to the operator are automotive power steering units, aircraft controllers and manipulators.

In general terms, a servo is any power-amplifying mechanism. Figure 55 is a basic hydromechanical servomechanism with internal position feedback but not including position and force feedback to the operator.

The system operates in the following manner. Suppose the operator moves his control handle an amount  $+x$  which displaces the valve spool from its centered

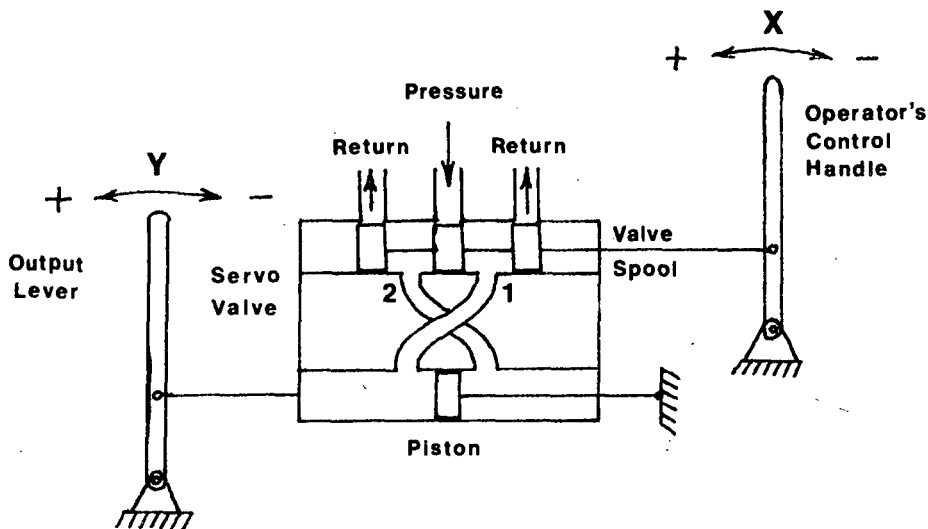


Figure 55: Hydraulic servomechanism with internal position feedback

position and causes fluid to flow thru passage 1. This forces the servomechanism to move to the left and produces the output displacement,  $+y$ . Because the servomechanism's motion is relative to valve spool position, the displacement of the servo automatically recenters the valve spool and stops the flow. This relative motion is the internal position feedback feature of this servo system.

The major limitation of this system is that the operator can move the control handle to its extreme position while waiting for the actuator to follow; and if the pressure source fails, he has no indication that the actuator is not moving. It is this lack of communication (no position or force feedback between the man and machine) that can be avoided if the system is modified so that it is bilateral in character, which means that position and force information is transmittable in either direction of the servo loop.

This reversibility of position and feel effect can be obtained in two ways: by fluid pressure or mechanically. Figure 56 shows a servomechanism similar to that depicted in Figure 55. However, this system is equipped with a cylinder to acquire force feedback by

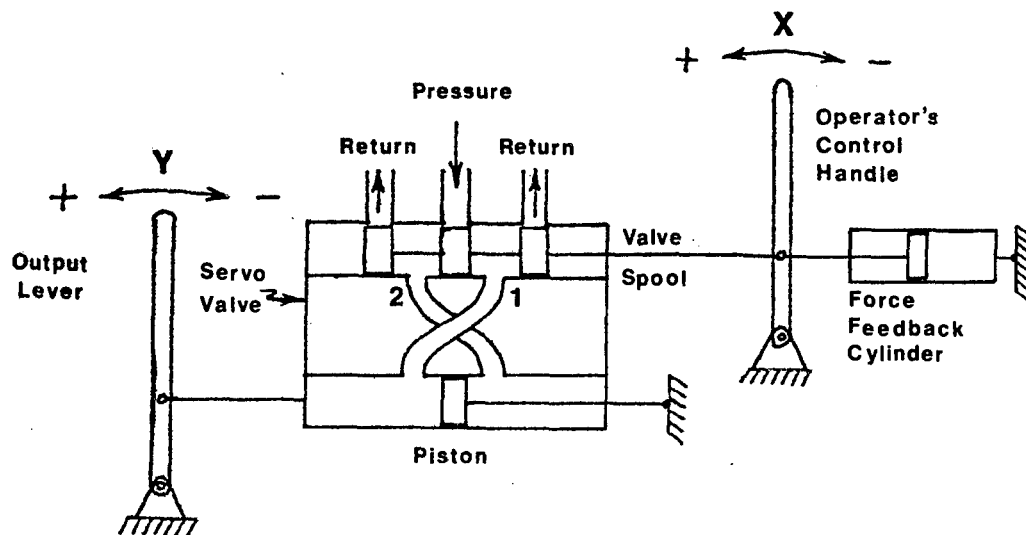


Figure 56: Hydraulic servomechanism with force feedback cylinder.

system fluid pressure. The degree of force felt by the operator is a function of the force feedback cylinder area and the linkage ratio. In some cases, the force feedback cylinder is incorporated inside the servo valve.

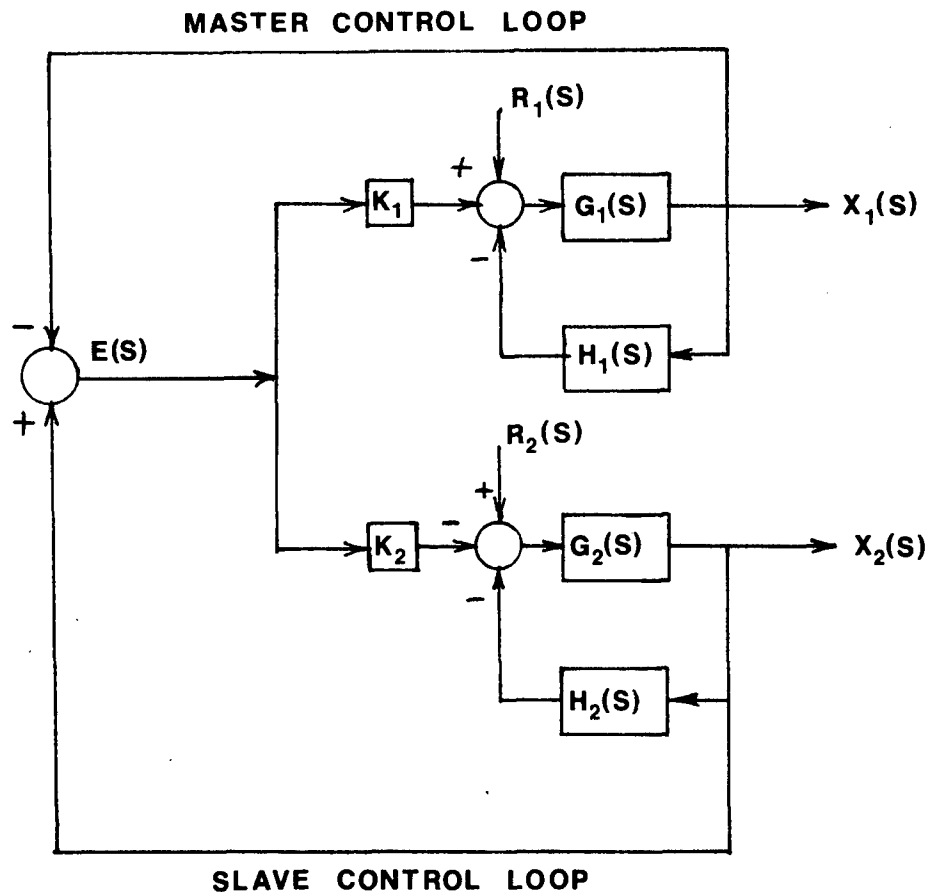
There are many possible physical arrangements to obtain this bilateral feature. In general, the bilateral feature is achieved by joining (in one loop) a pair of positional-error servomechanisms and connecting them in tandem so that error signals are common to both. Figure 5 illustrates the general block diagram for bilateral servomechanisms. The common error signal  $E(S)$  provides a direct means for reflecting slave forces back to the operator. In addition, a slight discrepancy in the spatial correspondence of master and slave will not only impart a corrective motion to the slave but will also transmit to the operator a feedback signal of an unbalanced force proportional to the amount of desynchronization.

Bilateral servo system operation involves three types of feedback: position, force (a function of position) and velocity. Position and velocity signals are monitored by sensors such as potentiometers and tachometers respectively and force is monitored by the operator's sense of feel.

There are a variety of control circuits and components available for the design and construction of bilateral servo systems. The designer's choice depends primarily on the operator and machine performance requirements. In addition, the machine configuration, size and performance characteristics dictate the type of components and energy source to be used. The combination of machine performance characteristics and human operator capabilities also influences the design.

The following are some of the factors that determine system and controller design with respect to operator requirements.

Deadband in position and force must be kept minimal and position accuracy must be maintained in order to



$G_1(S)$  : Open loop transfer function of master control loop  
 $G_2(S)$  : Open loop transfer function of slave control loop  
 $H_1(S)$  : Feedback transfer function of master control loop  
 $H_2(S)$  : " " " " slave " "  
 $K_1$  : Variable gain within master control loop  
 $K_2$  : " " " slave " "  
 $E(S)$  : Error signal  
 $X_1(S)$  : Output variable of master  
 $X_2(S)$  : " " " slave  
 $R_1(S)$  : Reference signal to master control loop  
 $R_2(S)$  : Reference " " slave " "

Figure 57: Bilateral Servo Block Diagram

avoid degradation of control accuracy. The system response must be crisp and compliance (the amount of deflection of master control with respect to slave) must be small. Increasing loop gain decreases the compliance factor. Force sensitivity or resolution is very critical for some operations. Friction forces will deteriorate the crispness of force reflection to the operator and tire the operator quickly. Viscous drag (a force which is proportional to velocity) is another force that significantly deteriorates the man's performance. Utilizing pressure feedback is one method to control the amount of viscous drag.

Force and position drift problems must always be compensated for. Drift is caused by any component that transmits information singularly to one end of the servo loop. Components that are common to both input and output circuit paths in the servo loop system will not cause drift, only a small desynchronization of position. Position desynchronization is usually minor when the system loop gain is very high.

The following analysis is intended to identify basic bilateral servo system criteria and to serve as a general guideline for the designer. The analysis will not go into pole-zero placement to achieve specific dynamic behavior; but to supplement the analysis, variations of circuits and related implications in design and performance will be discussed.

The system to be considered for analysis purposes is given by equations (1), (2) and (3):

$$J_1 \frac{d^2\theta_1}{dt^2} + f_1 \frac{d\theta_1}{dt} = K_1 E(t) + T_1(t) \quad (1)$$

$$J_2 \frac{d^2\theta_2}{dt^2} + f_2 \frac{d\theta_2}{dt} = -K_2 E(t) + T_2(t) \quad (2)$$

$$E(t) = \theta_2(t) - \theta_1(t) \quad (3)$$

where,

$J_{1,2}$  = represents master (slave) inertia

$f_{1,2}$  = represents master (slave) damping

$T_{1,2}$  = represents required master (slave) torque

$E(t)$  = corresponds to the error signal between  
 $\theta_1(t)$  and  $\theta_2(t)$  and

$K_{1,2}$  = control system gain terms

Equation (1) will be the dynamic equation of motion for the master control loop and equation (2) is the dynamic equation describing the slave control loop. Torque  $T_1(t)$  or angle  $\theta_1(t)$  may be considered the command input, that is, if  $T_1(t)$  is considered the operator's command input then  $\theta_1(t)$  is a function of the operator's applied torque or if  $\theta_1(t)$  is considered the operator's command input then  $T_1(t)$  is the operator's torque required to produce  $\theta_1(t)$ . Torque  $T_2(t)$  and angle  $\theta_2(t)$  may be considered the output variables for the system. For simplicity, static friction, position, velocity and force ratios between the slave and master sections of the system have been neglected.

For servo system stability analysis, it is best to describe the system in transfer function form and use block diagrams. By definition, when using Laplace transforms, the transfer function of a given system is the ratio of the output variable to the input variable assuming zero initial conditions. Thus, taking the laplace transform of equations (1), (2) and (3) results in:

$$(J_1 S^2 + f_1 S) \theta_1(S) = K_1 E(S) + T_1(S) + (J_1 S + f_1) \theta_1(0) + J_1 \dot{\theta}_1(0) \quad (4)$$

$$(J_2 S^2 + f_2 S) \theta_2(S) = -K_2 E(S) + T_2(S) + (J_2 S + f_2) \theta_2(0) + J_2 \dot{\theta}_2(0) \quad (5)$$

$$E(S) = \theta_2(S) - \theta_1(S) \quad (6)$$

Assuming the initial conditions equal to zero,

$$\theta_1(0) = \theta_2(0) = \dot{\theta}_1(0) = \dot{\theta}_2(0) = 0$$

equations (7), (8) and (9) represent the transfer functions for the master and slave control loops:

$$\frac{\theta_1(s)}{T_1(s)} = \frac{1}{(J_1 s^2 + f_1 s)} + \frac{K_1}{(J_1 s^2 + f_1 s)} \frac{E(s)}{T_1(s)} = G_1(s) + K_1 G_1(s) \frac{E(s)}{T_1(s)} \quad (7)$$

$$\frac{\theta_2(s)}{T_2(s)} = \frac{1}{(J_2 s^2 + f_2 s)} - \frac{K_2}{(J_2 s^2 + f_2 s)} \frac{E(s)}{T_2(s)} = G_2(s) + K_1 G_1(s) \frac{E(s)}{T_1(s)} \quad (8)$$

$$E(s) = \theta_2(s) - \theta_1(s)$$

$$G_1(s) = 1 / (J_1 s^2 + f_1 s) \quad (9)$$

$$G_2(s) = 1 / (J_2 s^2 + f_2 s)$$

Figure 58 represents the block diagram of the system given by equations (1), (2) and (3) using the notations of equations (7), (8) and (9).

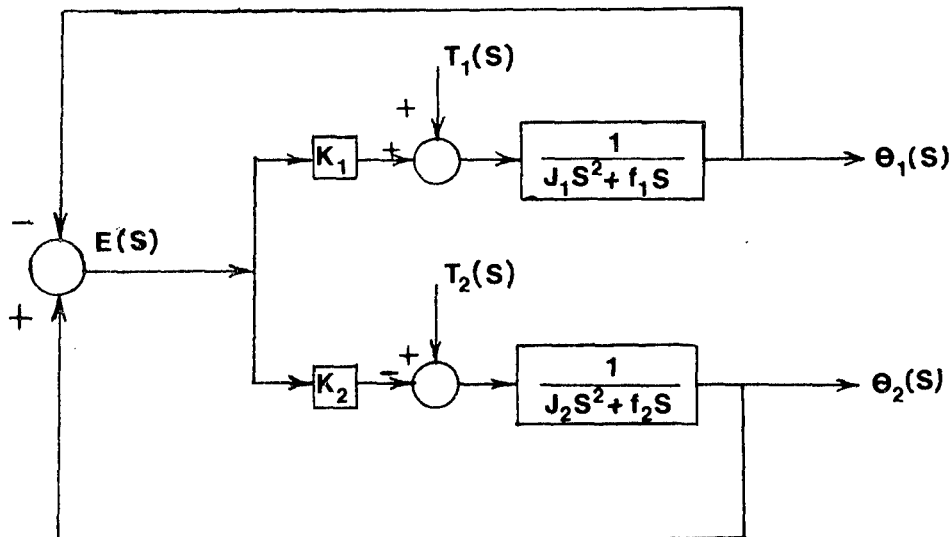


Figure 58: Block Diagram of System given by Equations (1), (2) and (3)



Note that when comparing Figure 58 to the bilateral servo block diagram given by Figure 57, Figure 58 has the same form except for the feedback loops with transfer functions  $H_1(S)$  and  $H_2(S)$ . Thus,  $H_1(S)$  and  $H_2(S)$  may or may not be required depending upon further servo system analysis for stability and response purposes. Therefore,  $H_1(S)$  and  $H_2(S)$  may be considered additional compensation networks necessary to achieve optimum response. Solving equations (4), (5) and (6) for  $\theta_1(S)$  and  $\theta_2(S)$  results in:

$$\theta_1(S) = \frac{[1+G_2(S)K_2] \left[ T_1(S)G_1(S) + \frac{\theta_1(0)}{S} + J_1G_1(S)\dot{\theta}_1(0) \right] + K_1G_1(S)[G_2(S)T_2(S) + \frac{\theta_2(0)}{S} + J_2G_2(S)\dot{\theta}_2(0)]}{1+K_1G_1(S) + K_2G_2(S)} \quad (10)$$

$$\theta_2(S) = \frac{[1+K_1G_1(S)] \left[ T_2(S)G_2(S) + \frac{\theta_2(0)}{S} + J_2G_2(S)\dot{\theta}_2(0) \right] + K_2G_2(S)[G_1(S)T_1(S) + \frac{\theta_1(0)}{S} + J_1G_1(S)\dot{\theta}_1(0)]}{1+K_1G_1(S) + K_2G_2(S)} \quad (11)$$

Note that these equations revert to the same expressions as would be obtained from the block diagram of Figure 58 if the initial conditions were assumed to be zero. Equations (10) and (11) represent the complete solution of the system.

For servo system stability analysis and synthesis, the initial conditions are assumed to be zero and the response of the system is investigated using controlled step or ramp inputs. Stability analysis is performed on the characteristic equation (the denominator of equations (10) and (11)) using either root locus, Bode or Nyquist techniques since the dynamical behavior of the system is dependent upon the roots of the characteristic equation. The roots of the characteristic equation are normally functions of the parameters and control gains within the system and as such, can be varied to achieve various response characteristics. Therefore, for stability analysis, one must examine the roots of the characteristic equation as a function of the parameters and variable gains within system. This is generally done using the root locus technique, Bode or Nyquist techniques are normally used for compensation purposes if it is determined

that variation of the systems parameters and gain are not enough to achieve the type of response desired.

It is interesting to note that if both the master and slave control loops are identical then:

$$K_1 G_1(S) = K_2 G_2(S)$$

and the characteristic equation then becomes:

$$1+2 K_1 G_1(S) = 1+2 K_2 G_2(S) .$$

This represents doubling the gain of the system and may result in an unstable and, hence, undesirable response. This basic point shows the increased complexity when trying to stabilize a bilateral servo system.

Because a bilateral servo system is usually composed of two servo control loops, one very important point to make is: when the master loop characteristics are much different than those of the slave loop, the dynamic effect of one loop on the other is much less. As an example as the slave mass becomes very large, such as in the case of the quadruped test bed, compared to the small mass of the corresponding master control, the response time of the slave is much larger than that of the master. Thus, the stabilizing factors needed for the master control loop are at a much higher frequency domain than those to which the slave control loop can respond. Therefore, stabilizing the master can be done with more freedom without adversely affecting the secondary slave loop. It also follows that stabilizing networks used for a large slave loop usually have very little adverse effect on the master stability which, in turn, is to be controlled at a much higher frequency.

The analog computer analysis techniques defined in the article given in the Bibliography, Section IV, Number 103 will be used as a basis for the bilateral servo loop synthesis techniques presented below.

Prior to the synthesis of any system, the characteristics of the existing system must be investigated. The amount of

position desynchronization of master and slave due to an initial displacement at time  $t=0$  can be investigated using equations (10) and (11), the final value theorem of Laplace transform theory and assuming the following initial conditions  $T_1(t) = T_2(t) = \dot{\theta}_1(0) = \dot{\theta}_2(0) = 0$ . Recalling the final value theorem: if the  $\lim_{t \rightarrow \infty} F(t)$  exists, then  $\lim_{s \rightarrow 0} sF(s) = \lim_{t \rightarrow \infty} F(t)$ , using the above assumption and defining the initial displacement condition as

$$\theta_1(0) = \theta_1$$

$$\theta_2(0) = 0,$$

equations (10) and (11) reduce to

$$\theta_1(s) = \frac{1 + K_2 G_2(s)}{1 + K_1 G_1(s) + K_2 G_2(s)} \frac{\theta_1}{s} \quad (12)$$

$$\theta_2(s) = \frac{(K_2 G_2(s))}{1 + K_1 G_1(s) + K_2 G_2(s)} \frac{\theta_1}{s} \quad (13)$$

Employing the final value theorem to equations (12) and (13) results in:

$$\lim_{t \rightarrow \infty} \theta_1(t) = \lim_{s \rightarrow 0} s \theta_1(s) = \lim_{s \rightarrow 0} s \frac{[1 + K_2 G_2(s)]}{1 + K_1 G_1(s) + K_2 G_2(s)} \frac{\theta_1}{s}$$

$$\theta_1|_{ss} = \lim_{s \rightarrow 0} \frac{\theta_1}{1 + \frac{K_1 G_1(s)}{1 + K_2 G_2(s)}} = \lim_{s \rightarrow 0} \frac{\theta_1}{1 + \frac{K_1}{\frac{J_1 s^2 + f_1 s}{1 + \frac{K_2}{J_2 s^2 + f_2 s}}}}$$

$$(14)$$

$$\theta_1|_{ss} = \lim_{s \rightarrow 0} \frac{\theta_1}{1 + \frac{K_1}{\frac{J_1 s + f_1}{s + \frac{K_2}{J_2 s + f_2}}}} = \frac{K_2 f_1 \theta_1}{K_2 f_1 + K_1 f_2}$$

and similarly,

$$\lim_{t \rightarrow \infty} \theta_2(t) = \lim_{s \rightarrow 0} s \theta_2(s) = \lim_{s \rightarrow 0} s \left\{ \frac{K_2 G_2(s) \frac{\theta_1}{s}}{1 + K_1 G_1(s) + K_2 G_2(s)} \right\}$$

$$\theta_2 |_{ss} = \lim_{s \rightarrow 0} \left\{ \frac{\frac{K_2}{J_2 s^2 + f_2 s} \theta_1}{1 + \frac{K_1}{J_1 s^2 + f_1 s} + \frac{K_2}{J_2 s^2 + f_2 s}} \right\} \quad (15)$$

$$\theta_2 |_{ss} = \lim_{s \rightarrow 0} \frac{\frac{K_2 \theta_1}{J_2 s + f_2}}{s + \frac{K_1}{J_1 s + f_1} + \frac{K_2}{J_2 s + f_2}} = \frac{K_2 f_1 \theta_1}{K_2 f_1 + K_1 f_2}$$

It is easily seen when substituting equations (14) and (15) into equation (9) that there is zero error desynchronization in position due to an initial displacement in position. In a similar manner, bilateral servo force drift and viscous drag effects can be identified when assuming the following initial conditions:

$$\theta_1(0) = \theta_2(0) = \dot{\theta}_1(0) = \dot{\theta}_2(0) = 0$$

and applied torque condition

$$T_1(s) = 0$$

$$T_2(s) = \frac{T_2}{s}$$

Substituting these conditions into equations (10) and (11) results in:

$$\theta_1(s) = \frac{K_1 G_1(s) G_2(s) \frac{T_2}{s}}{1 + K_1 G_1(s) + K_2 G_2(s)} \quad (16)$$

$$\theta_2(s) = \frac{1 + K_1 G_1(s) \quad G_2(s) \quad \frac{T_2}{s}}{1 + K_1 G_1(s) + K_2 G_2(s)} \quad (17)$$

Simplifying,

$$\theta_1(s) = \frac{K_1 T_2}{s^2 [s(J_1 s + f_1)(J_2 s + f_2) + K_1(J_2 s + f_2) + K_2(J_1 s + f_1)]} \quad (18)$$

$$\theta_2(s) = \frac{(s^2 J_1 + s f_1 + K_1) T_2}{s^2 [s(J_1 s + f_1)(J_2 s + f_2) + K_1(J_2 s + f_2) + K_2(J_1 s + f_1)]} \quad (19)$$

and employing the final value theorem results in the following steady-state condition:

$$\lim_{s \rightarrow 0} s \theta_1(s) = \lim_{t \rightarrow \infty} \theta_1(t) = \infty \quad (20)$$

$$\lim_{s \rightarrow 0} s \theta_2(s) = \lim_{t \rightarrow \infty} \theta_2(t) = \infty \quad (21)$$

These equations show that a step function of torque applied to either of the control loops (which may be a result of an applied force due to dead weight, etc.) results in unlimited motion at each shaft. Thus, if there is a torque created by dead weight, the operator would need to supply a bias torque at the operators station continuously to overcome the torque and maintain the desired position. This result points out the necessity to match the applied torques to the master and slave control loops. Therefore, again assuming zero initial conditions

$$\theta_1(0) = \theta_2(0) = \dot{\theta}_1(0) = \dot{\theta}_2(0) = 0$$

and torque inputs to the master and slave control loops

$$T_1(s) = \frac{T_1}{s}$$

$$T_2(s) = \frac{T_2}{s}$$

the following expressions are obtained for  $\theta_1(s)$  and  $\theta_2(s)$ :

$$\theta_1(s) = \frac{[1+K_2G_2(s)] G_1(s) \frac{T_1}{s} + K_1G_1(s)G_2(s) \frac{T_2}{s}}{1 + K_1G_1(s) + K_2G_2(s)} \quad (22)$$

$$\theta_2(s) = \frac{[1+K_1G_1(s)] G_2(s) \frac{T_2}{s} + K_2G_2(s)G_1(s) \frac{T_1}{s}}{1 + K_1G_1(s) + K_2G_2(s)} \quad (23)$$

Expanding equations (22) and (23) result in:

$$\theta_1(s) = \frac{(J_2s^2+f_2s+K_2) \frac{T_1}{s} + \frac{K_1T_2}{s}}{(J_2s^2+f_2s)(J_1s^2+f_1s) + K_1(J_2s^2+f_2s) + K_2(J_1s^2+f_1s)} \quad (24)$$

$$\theta_2(s) = \frac{(J_1s^2+f_1s+K_1) \frac{T_2}{s} + \frac{K_2T_1}{s}}{(J_2s^2+f_2s)(J_1s^2+f_1s)+K_1(J_2s^2+f_2s) + K_2(J_1s^2+f_1s)} \quad (25)$$

It is seen that when employing the final value theorem to equations (24) and (25) the infinite position condition still exists. However, if the parameters are chosen such that the following condition holds

$$K_1T_2 = -K_2T_1 \quad (26)$$

when  $T_1$  and  $T_2$  are of opposite sign, then employing the final value theorem results in:

$$\lim_{s \rightarrow 0} s\theta_1(s) = \frac{-s \left\{ s(J_2s + f_2) \frac{T_1}{s} \right\}}{(J_1s^2+f_1s)(J_2s^2+f_2s)+K_1(J_2s^2+f_2s)+K_2(J_1s^2+f_1s)} \quad (27)$$

$$\theta_1|_{ss} = \frac{-f_2T_1}{K_1f_2 + K_2f_1}$$

and

$$\lim_{s \rightarrow 0} s \theta_2(s) = \frac{s \left\{ s(J_1 s + f_1) \frac{T_2}{s} \right\}}{(J_1 s^2 + f_1 s)(J_2 s^2 + f_2 s) + K_1(J_2 s^2 + f_2 s) + K_2(J_1 s^2 + f_1 s)} \quad (28)$$

$$\theta_2|_{ss} = \frac{f_1 T_2}{K_1 f_2 + K_2 f_1}$$

which demonstrates that it is possible to achieve finite displacement in position when the operator applies a negative torque to the master. However, the displacements are out of phase. To determine if it is possible to achieve one to one correspondence in position by adjusting parameters within the system, the equation for error must be investigated:

$$\lim_{s \rightarrow 0} s E(s) = \lim_{s \rightarrow 0} s \left\{ \theta_2(s) - \theta_1(s) \right\} = \frac{f_1 T_2 + f_2 T_1}{K_1 f_2 + K_2 f_1} \quad (29)$$

Note that if:

$$K_1 > 0$$

$$K_2 > 0$$

$$T_2 > 0$$

and

$$T_1 < 0$$

the only possible way to achieve zero steady-state error without further system modification is for  $f_1$  or  $f_2$  to be less than zero. With  $f_1 < 0$  it is seen that there is now one to one correspondence in position. At first glance there appears to be no problems and zero steady-state error, however, the consequences of  $f_1 < 0$  (or  $f_2 > 0$ ) must be investigated. First, when looking at equations (1), (2) and (3), it is apparent that if  $f_1 < 0$  or  $f_2 > 0$ , negative damping is required which is not possible physically. Furthermore, when examining the conditions:

$$\frac{K_1}{K_2} = \frac{-T_1}{T_2}$$

$$\text{and} \quad \frac{-f_1}{f_2} = \frac{T_1}{T_2}$$

then  $K_1 f_2 = K_2 f_1$

which implies that the sum  $K_1 f_2 - K_2 f_1 = 0$

and the error expression is now in an indeterminate form:

$$E|_{ss} = \frac{f_2 T_1 - f_1 T_2}{K_1 f_2 - K_2 f_1} = \frac{0}{0}$$

Thus, to ascertain the consequence of this, the characteristic equation must be examined for roots with positive real parts to determine instability. With  $T_1 < 0$  and  $f_1 < 0$ ,

$$\theta_2(s) = \frac{-(J_1 s^2 - f_1 s) \frac{T_1}{s}}{J_1 J_2 s^4 + (J_1 f_2 - J_2 f_1) s^3 + (K_1 J_2 + K_2 J_1 - f_1 f_2) s^2 + (K_1 f_2 - K_2 f_1) s}$$

the characteristic equation, which is a polynomial in  $s$ , has negative coefficients. From Hurwitz's criterion, if not all the coefficients are positive, then there are roots with positive real parts. Therefore, the system as it stands with  $f_{1,2} < 0$ , is unstable. It is impossible to achieve both zero steady-state error and finite position by adjustment of  $K_{1,2}$  or  $f_{1,2}$  alone and the system as it stands will require further compensation networks. Referring to Figures 57 and 58, the obvious place to start adding compensation networks is in the feedback loops containing  $H_1(s)$  and  $H_2(s)$ . It is recommended to first try position feedback, as this is the simplest form of compensation, to try and obtain the desired response. Therefore, let  $H_1(s) = H_1$  and  $H_2(s) = H_2$  be adjustable feedback gains in position. Using these new variables, the system is now represented by Figure 59.

From Figure 59 is is readily determined that:

$$\theta_1(s) = \frac{[J_2 s^2 + f_2 s + K_2 + H_2] T_1(s) + K_1 T_2(s)}{[J_1 s^2 + f_1 s + H_1][J_2 s^2 + f_2 s + H_2] + K_1 [J_2 s^2 + f_2 s + H_2] + K_2 [J_1 s^2 + f_1 s + H_1]} \quad (30)$$



$$\theta_2(s) = \frac{J_1 s^2 + f_1 s + K_1 + H_1}{J_1 s^2 + f_1 s + H_1} \frac{T_2(s)}{J_2 s^2 + f_2 s + H_2 + K_1} + \frac{K_2 T_1(s)}{J_2 s^2 + f_2 s + H_2 + K_2} \frac{1}{J_1 s^2 + f_1 s + H_1} \quad (31)$$

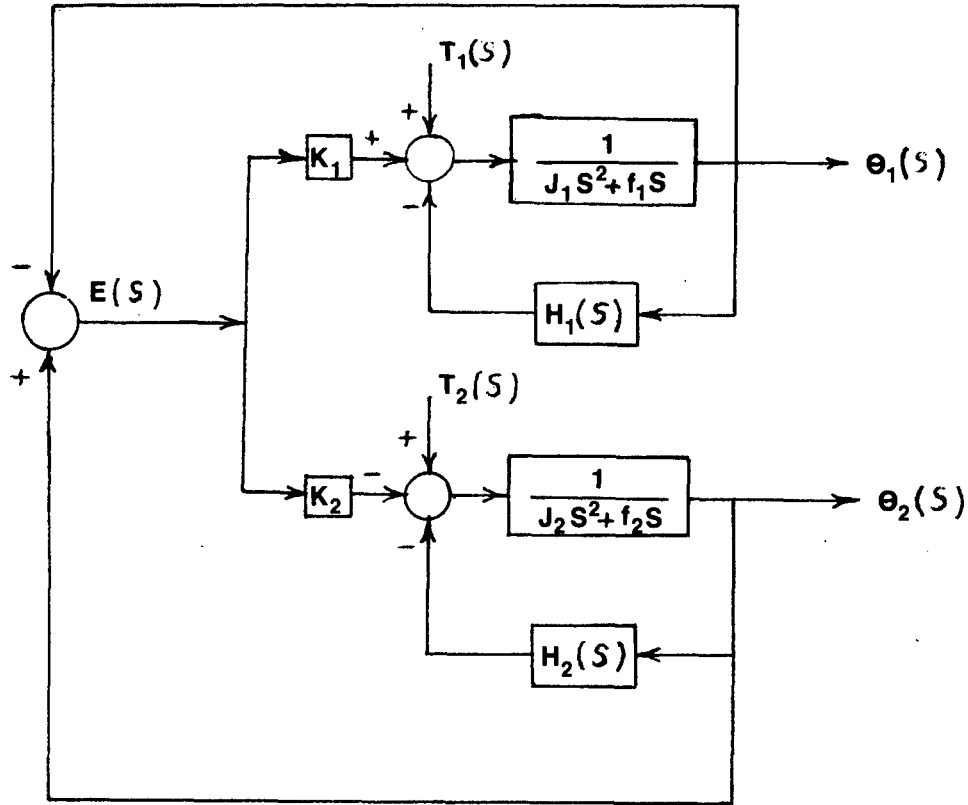


Figure 59: Bilateral Servo System with Position Feedback Compensation

Employing the final value theorem assuming  $T_1(s) = \frac{T_1}{s}$   
and  $T_2(s) = \frac{T_2}{s}$

results in

$$\theta_1(s) = \frac{(K_2 + H_2) T_1 + K_1 T_2}{H_1 H_2 + K_1 H_2 + K_2 H_1} \quad (32)$$

$$\theta_2(s) = \frac{(K_1 + H_1) T_2 + K_2 T_1}{H_1 H_2 + K_1 H_2 + K_2 H_1} \quad (33)$$

Finding  $E(s)$  ss

$$E|_{ss} = \frac{H_1 T_2 - H_2 T_1}{H_1 H_2 + K_1 H_2 + K_2 H_1} \quad (34)$$

it is seen that when  $H_1 T_2 = H_2 T_1$ , the system will have zero steady-state error and finite displacement in position for torque inputs. The major result or consequence of adding position feedback is that zero steady-state error and finite displacement may be obtained by adjusting the two parameters; and the dynamics of the system can be varied as a function of  $K_{1,2}$  and  $f_{1,2}$ .

It should be noted that the value of the damping terms,  $f_{1,2}$  is a critical factor for regulating the amount of system overshoot and settling time, and that the values of  $K_{1,2}$  regulates the compliance of the system. The inertia terms,  $J_{1,2}$  influences system behavior, however, there is usually little control over this parameter. Thus, the proper choice of components is crucial and should be selected with these critical parameters in mind.

The preceding analysis neglected the affects of changing inertias and loads within the system. This is a very important consideration in the design of control systems. For example, at the masters station, the operators hand on a control handle provides considerable damping and reflects a change in inertia to the servo loop. At the slave end, the load actually varies considerably depending on the workloads encountered and when the output contacts an immovable object, the servo experiences an extreme value for inertia. This represents an infinite load impedance to the system.

The foregoing approach for bilateral servo analysis provided an overview of the key design parameters to be

considered. The analysis outlined how one could analyze the steady-state conditions of the system and employ simple position feedback compensation to obtain satisfactory steady-state behavior. However, there are a multitude of second order effects that must be carefully understood and analyzed by the designer to achieve satisfactory transient behavior. This was implied by the statement that the dynamic response of the system could be varied by careful selection of the parameters  $f_{1,2}$  and  $K_{1,2}$ . These parameters are governed by the basic open loop transfer functions of the control system components. Therefore, a brief review of typical hydraulic servo components and their transfer functions will be made next to identify where these parameters can be varied and/or specified.

Figure 60 is a schematic diagram of the hydraulic components, linkage arrangement and simplified block diagram of a typical hydraulic linear actuator. The detailed block diagram and transfer function will be derived using a linear conservation of flow analysis.

Applying the principle of conservation of flow, total flow from the servo valve is:

$$Q_v = Q_c + Q_L + Q_p \quad (35)$$

where,

$Q_v$  = flow from servo valve ( $\text{in}^3/\text{sec}$ )

$Q_c$  = flow due to compressibility ( $\text{in}^3/\text{sec}$ )

$Q_L$  = flow due to leakage ( $\text{in}^3/\text{sec}$ )

$Q_p$  = flow due to power piston displacement ( $\text{in}^3/\text{sec}$ )

Using the following linear relationships which may be obtained from Ref (3),

$$Q_v = Q_o E$$

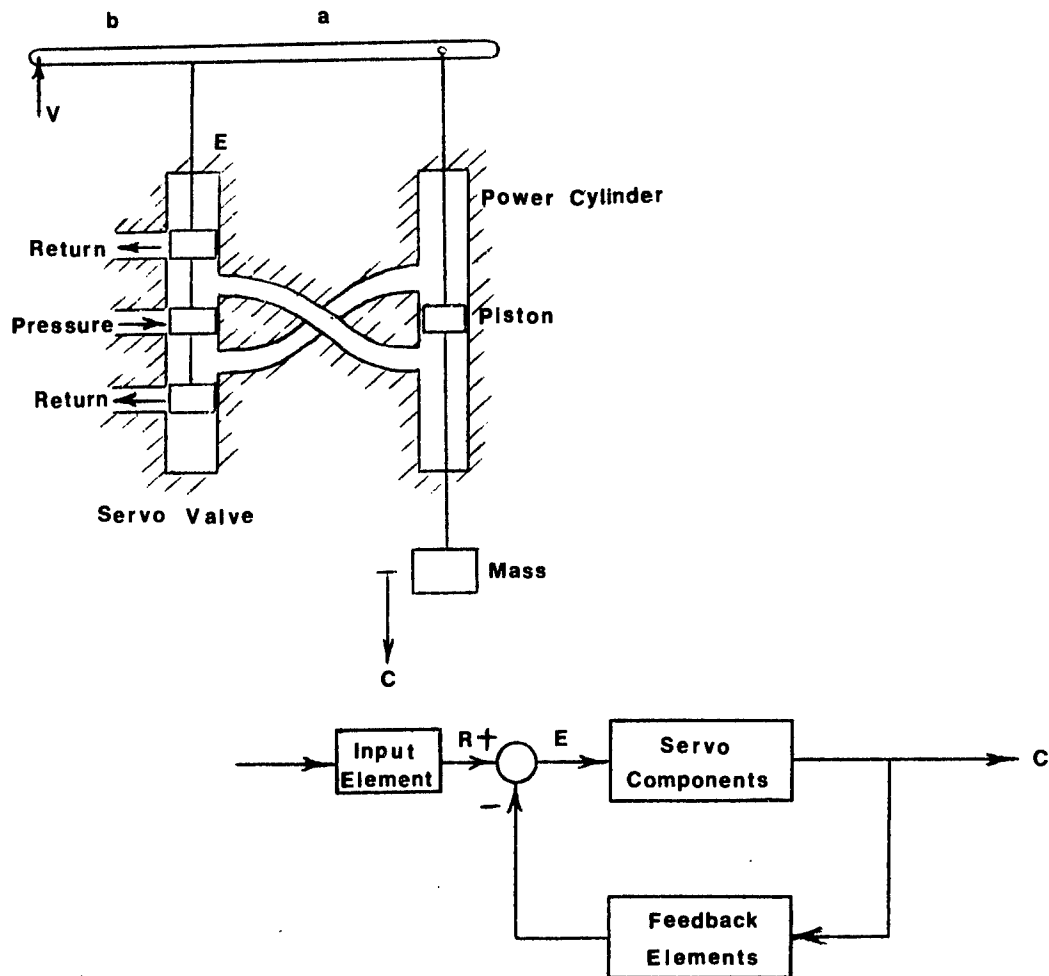


Figure 60: Hydraulic Servo System

$$Q_L = L \Delta P$$

$$\Delta P = \frac{2B}{V_O S} Q_c$$

$$Q_p = ASC$$

$$E = R - F$$

$$R = \frac{a}{a+b} V$$

$$F = \frac{b}{a+b} C$$

$$MCS^2 = \Delta PA$$

where,

E = error signal

L = leakage coefficient (in<sup>3</sup>/sec)/psi

B = bulk modulus of fluid, psi

V<sub>O</sub> = entrained volume of line, in<sup>3</sup>

Q<sub>O</sub> = valve flow gradient (in<sup>3</sup>/sec)/in

ΔP = pressure differential, psi

A = area of piston, in<sup>2</sup>

V = input travel, in

C = output travel, in

a,b = linkage dimensions, in

M = mass = slugs

S = complex operator, sec<sup>-1</sup>

and placing them in equation (35) results in Figure 61 which is a detailed block diagram of the linear actuator shown in Figure 60.

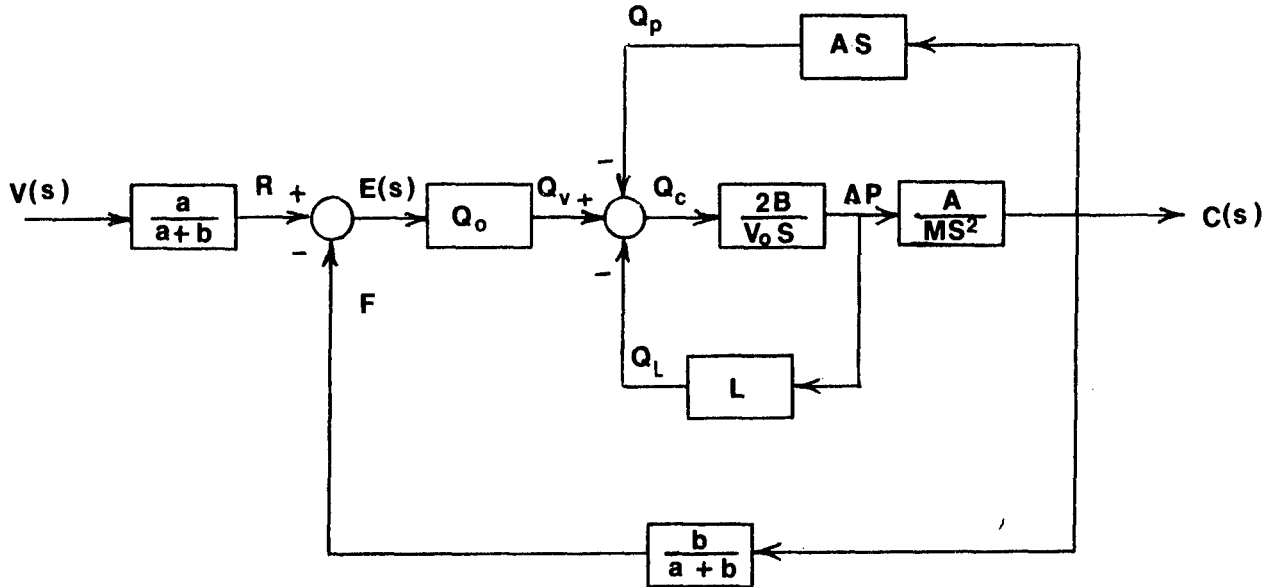


Figure 61: Detailed Block Diagram of Hydraulic Linear Actuator

From Figure 61, the open loop transfer function describing this system is given by:

$$\frac{C(S)}{E(S)} = \frac{Q_o/AS}{\frac{VM}{2BA^2} s^2 + \frac{LMS}{A^2} + 1} \quad (36)$$

Using the standard second order notation:

$$\frac{VMS^2}{2BA^2} + \frac{LMS}{A^2} + 1 = \frac{1}{W_n^2} s^2 + \frac{2\zeta}{W_n} s + 1 \quad (37)$$

it is readily seen that the natural frequency and damping ratio of the system is given by

$$W_n = \frac{2BA^2}{VM} \quad (38)$$

$$\zeta = \frac{L^2MB}{2VA^2} \quad (39)$$

Equations (38) and (39) identify the design parameters which affect the natural frequency and damping ratio of the system under consideration and as such, must be properly chosen to assure good response characteristics.

For illustrative purposes, the underdamped and overdamped case will be considered using different values for the leakage coefficient. This will affect the damping ratio, the roots of the characteristic equation and degree of stability of the system. Using the following numerical values:

$$A = 3 \text{ in}^2$$

$$B = 100,000 \text{ psi}$$

$$M = 300 \text{ lb sec}^2/\text{in}$$

$$V = 30 \text{ in}^3$$

$$Q_o = 1600 \text{ (in}^3/\text{sec)}/\text{in}$$

$L = .001 \text{ (in}^3/\text{sec)}/\text{psi}$  or  $.01 \text{ (in}^3/\text{sec)}/\text{psi}$  for the underdamped and overdamped case respectively and substituting these values into the open loop transfer function given by equation (36) results in

$$\frac{C(S)}{E(S)} = \frac{533}{s \left\{ \frac{s^2}{(14.14)^2} + \frac{(2)(.24)}{14.14} s + 1 \right\}} \quad (\text{underdamped}) \quad (40)$$

with  $W_n = 14.14 \text{ rad/sec}$  and  $\xi = 0.24$

$$\text{and} \quad \frac{C(S)}{E(S)} = \frac{533}{s \left\{ \frac{s^2}{(14.14)^2} + \frac{(2)(2.4)}{14.14} s + 1 \right\}} \quad (41)$$

$$\frac{C(S)}{E(S)} = \frac{533}{s \left\{ \frac{s}{3.09} + 1 \right\} \left\{ \frac{s}{64.78} + 1 \right\}} \quad (\text{overdamped})$$

with  $W_n = 14.14$  rad/sec and  $\xi = 2.40$ . Figures 62 and 63 are bode plots of the transfer functions given by equations (40) and (41) respectively. Without going into servo system stability theory, we simply state that if equation (40) represents the transfer function  $G_2(S)$  of Figure 57, the slave control loop will be unstable unless the magnitude of  $H_2(S)$  is less than .0125. This implies that the ratio should satisfy the following inequality:

$$\frac{b}{a+b} \leq 0.0125.$$

Similarly, if equation (41) represents the transfer function  $G_2(S)$  of Figure 57, the slave control loop will be unstable unless the magnitude of the  $H_2(S)$  is less than 0.1. This implies that:

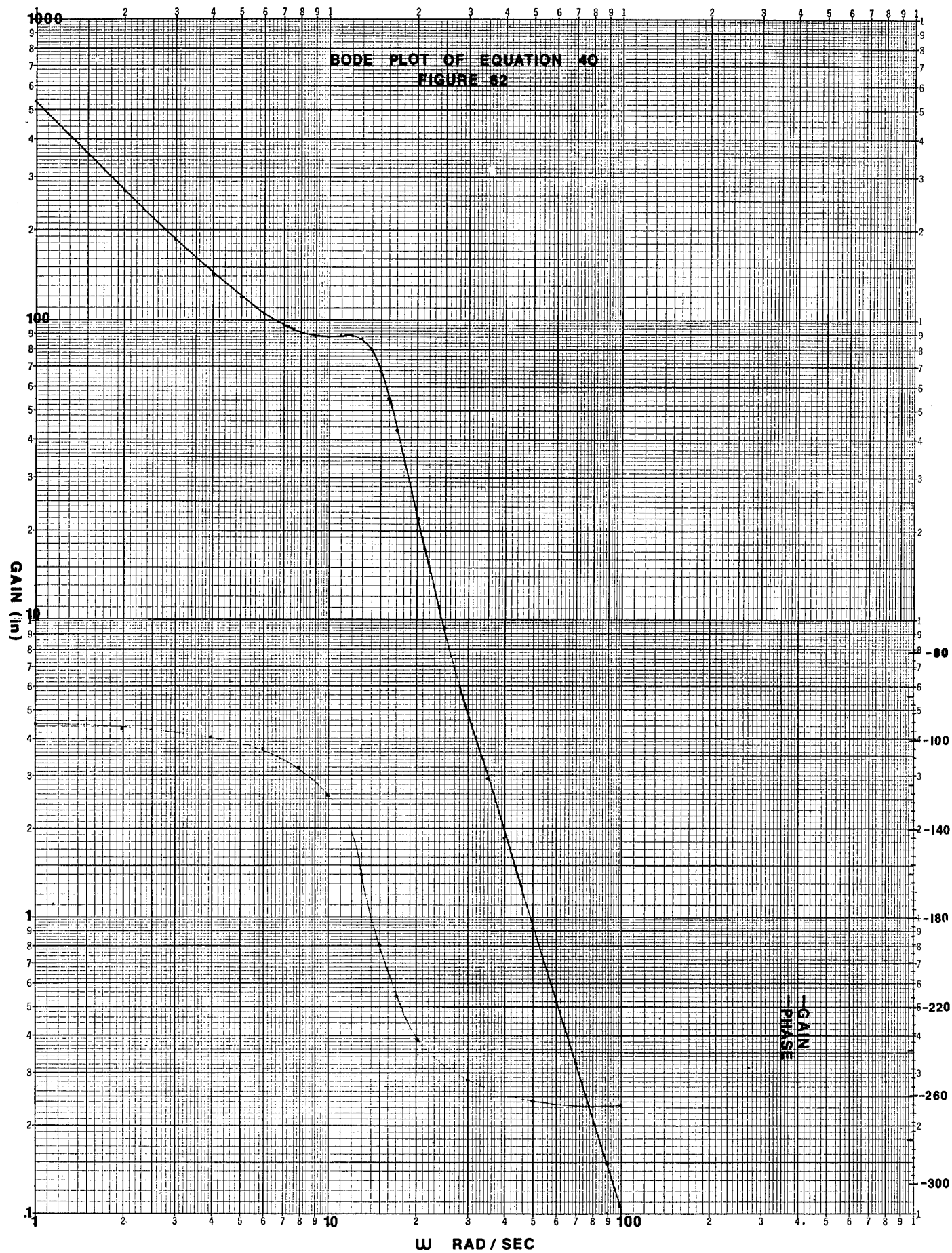
$$\frac{b}{a+b} \leq 0.1$$

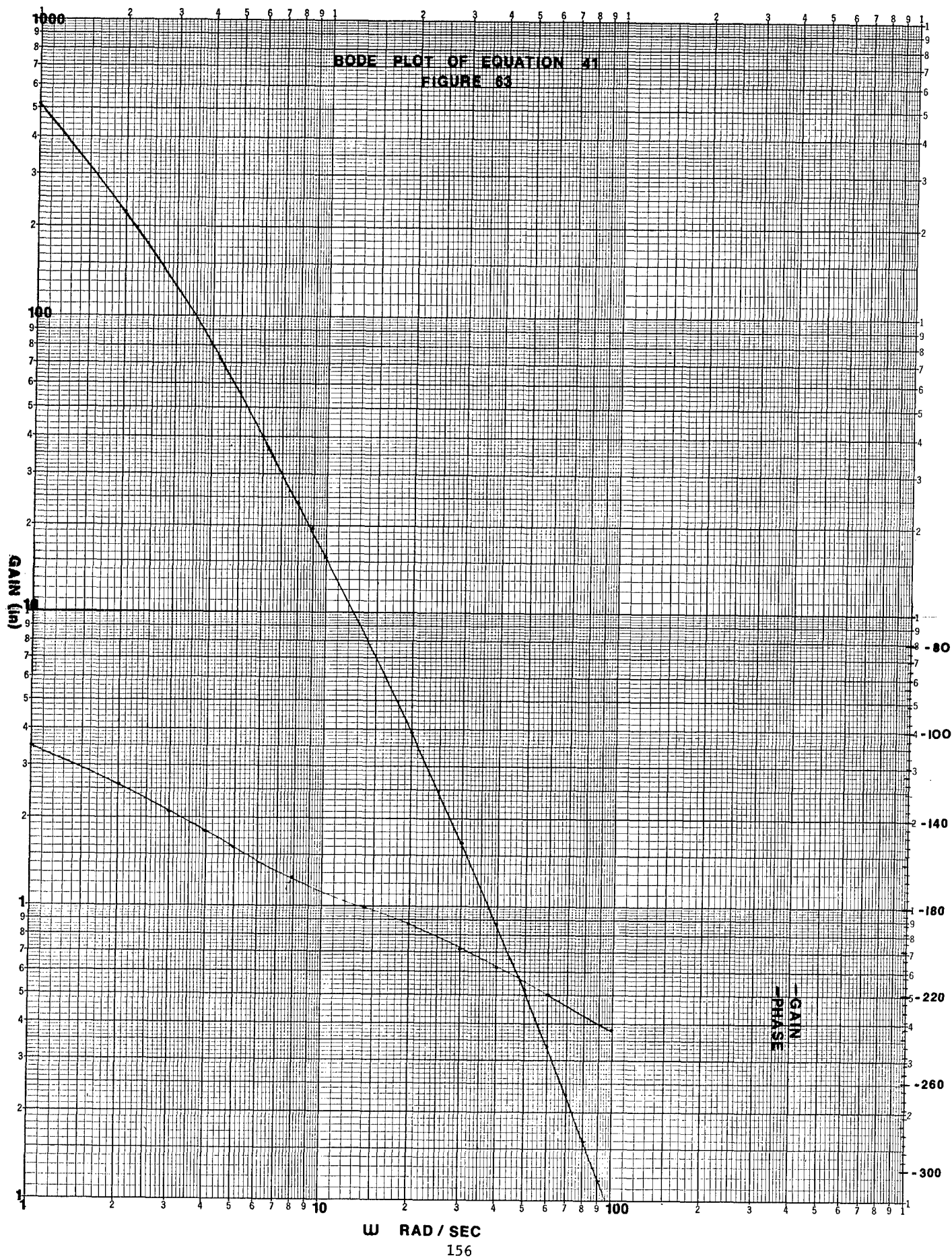
should hold.

The reference by Lewis and Stern shows various ways of providing mechanical and hydraulic stability functions for synthesizing hydraulic servo systems when simple gain adjustment is unsatisfactory. Stabilizing servo systems with hydraulic components that provide more complex stability functions, such as derivative and integral control, is more complex than using electrical subsystems, however, depending upon the application there may be no other way except to do so.

Figure 65 is a schematic diagram of a typical electro-hydraulic flow type servo valve and Figure 64 is a schematic diagram of a typical electrohydraulic pressure feedback servo valve. Pressure type servo valves are used wherever load resonance is a problem as in the case of antenna positioning systems, tank turret controls and bilateral servo systems. These valves provide the damping for the system so that resonance no longer predominates in the load response. The bode plot of Figure 63 has a slope of 40 db per decade and is a typical representation of a pressure feedback servo valve.







To implement pressure feedback, pressure is applied to an additional pair of areas on the valve spool, so that valve flow is reduced as a function of load pressure drop. The sizes of the spool end areas, flow metering slots, and centering springs can be selected to provide any desired system damping characteristics. If the spool and springs are removed altogether, the sensitivity of flow to pressure becomes nearly infinite. The result is a pressure control servo valve that regulates load differential pressure in response to input signals.

Figure 66, 67 and 68 describe typical dynamic characteristics for the pressure control servo valves. In Figure 66, the slope of the curve, which is pressure gradient with respect to change in current, is decreased considerably as a result of the pressure feedback feature. This provides a distinct stabilizing characteristic. In Figure 67, the slopes of the curves shown are the ratio of flow with respect to load pressure and are defined as the leakage co-efficient. Implementing pressure feedback increases these slopes which is equivalent to increasing system damping and reducing system overshoot and resonance behavior. Figure 68 is a typical frequency response diagram for an electro-hydraulic servo valve. It is important for servo valves to have a high frequency response so that the time constants of the servo valve's transfer function does not become a significant part of the overall system stability problem.

Figure 69 is the general block diagram of the quadruped test bed servo system. The number affixed to each block is explained below:

Block 1 is a hydraulic pressure generator and its output pressure is a function of the position error between master and slave. The pressure generated by Block 1 is the reference signal for Blocks 2 and 5. Both blocks 2 and 5 are referred to as pressure repeaters and will maintain an output pressure equal to the input reference pressure of Block 1 while providing the power

## Pressure Versus Flow Type Electro Hydraulic Servo Valves

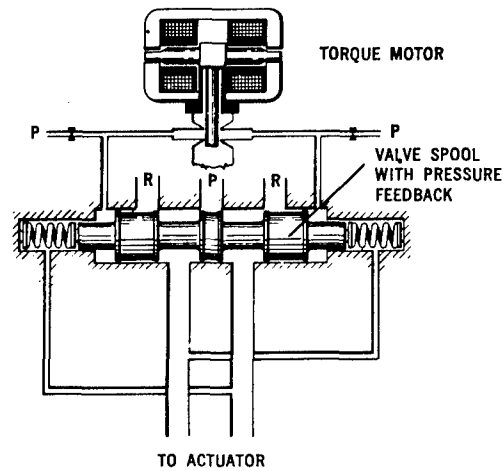


Figure 64: Schematic of Flow Type Electrohydraulic Servo Valve

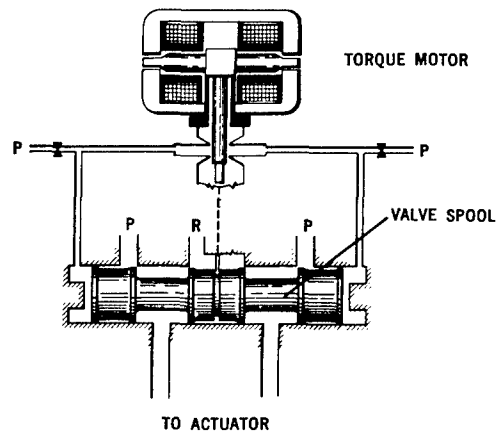


Figure 65: Schematic of Pressure Type Electrohydraulic Servo Valve

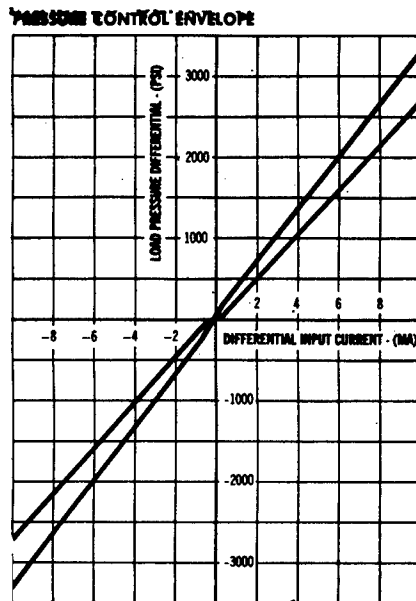


Figure 66: Servo Valve Pressure Gradient

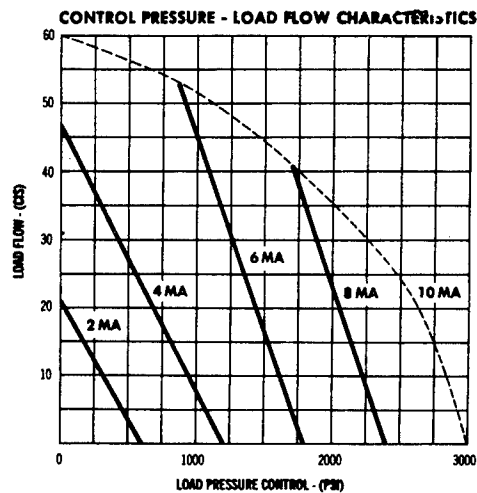


Figure 67: Servo Valve Flow Gradient

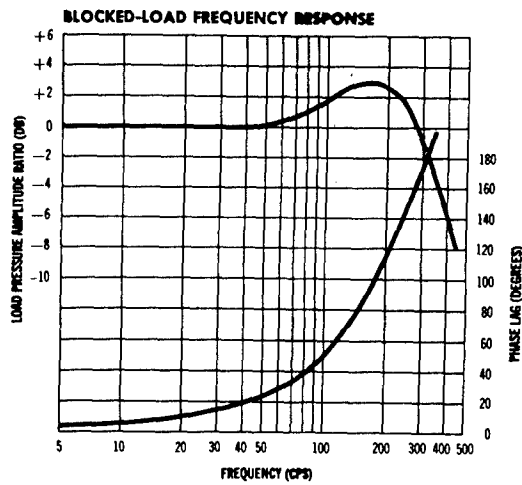


Figure 68: Servo Valve Frequency Response

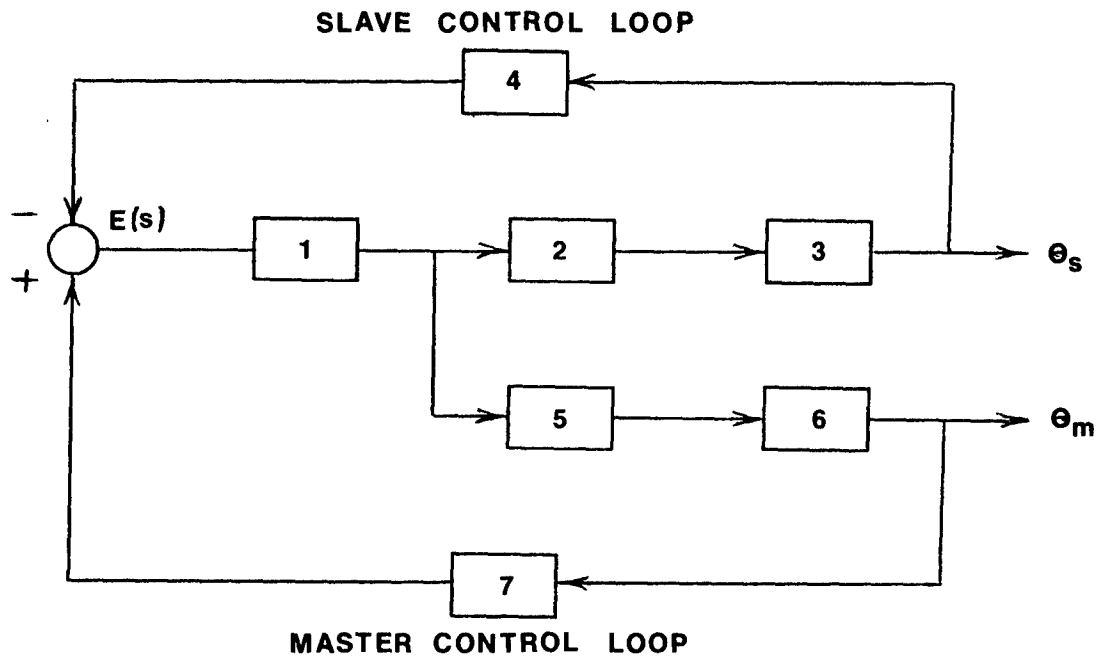


Figure 69 : Block Diagram of Quadruped Test Bed Bilateral Servo System

to activate the master and slave servo systems. Block 3 is the mass of the slave circuit and Block 6 is the mass of the master circuit. Block 4 is the mechanical linkage subsystem that reflects the output motion of the slave back to a summing point where it is compared to the corresponding signal of the mechanical linkage subsystem, Block 7, of the master. The difference between the signals of Blocks 4 and 7 results in the error signal which drives Block 1.  $\theta_s$  and  $\theta_m$  correspond to the angular rotation of the slave and master servo systems respectively. Details of this circuit design are described in the Fourth Progress Report on the Quadruped Test Bed Contract: DA20-113-AMC-09225(T). A technical discussion of this system is described in Appendix II of this report.

Figures 70 71 and 72 are the detailed component, symbolic and computer bilateral servo block diagrams of the Quadruped Test Bed respectively. They are included for completeness and to illustrate the type of subsystems used for the control of one joint only. Also included is the glossary of terms used within these block diagrams.

The system was designed to be all hydromechanical without the use of the usual electronic controls. This type of control was developed for the purpose of developing very simple, rugged, bilateral servos that could be easily maintained by inexperienced field service personnel. The cost of developing this kind of high performance all-hydromechanical servo equipment is more than that of a system which involves electronic equipment. The reason for this is the difficulty in stabilizing high performance systems with hydraulic and mechanical means.

The remainder of this chapter is a discussion of the factors which influence design of bilateral servo systems and reiterates briefly some of the items discussed above.

It was shown that for a symmetrical bilateral servo system, the forward loop gain of the system is doubled.

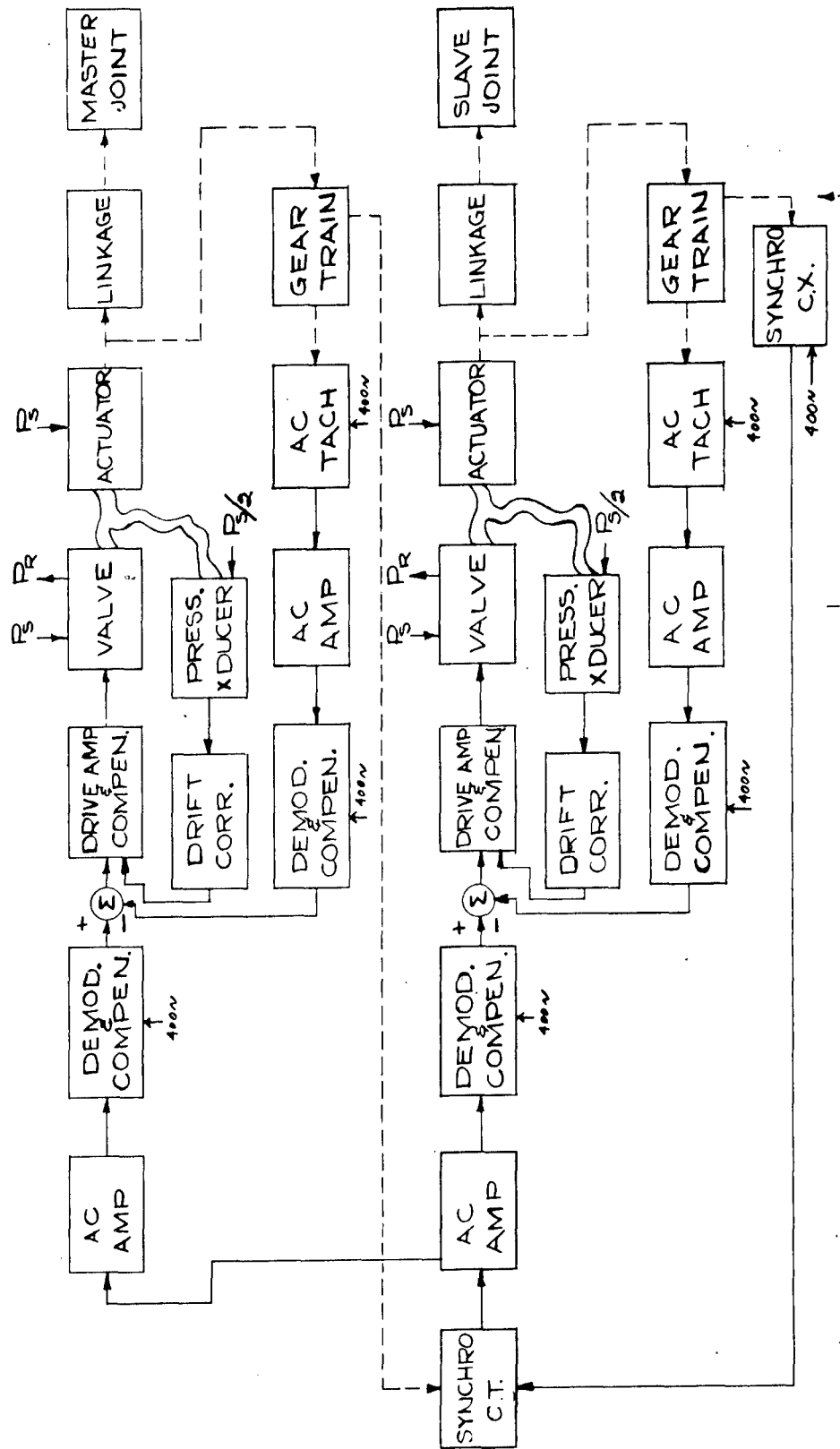


Figure 70: Component Diagram of Bilateral Servo



ONE JOINT ONLY

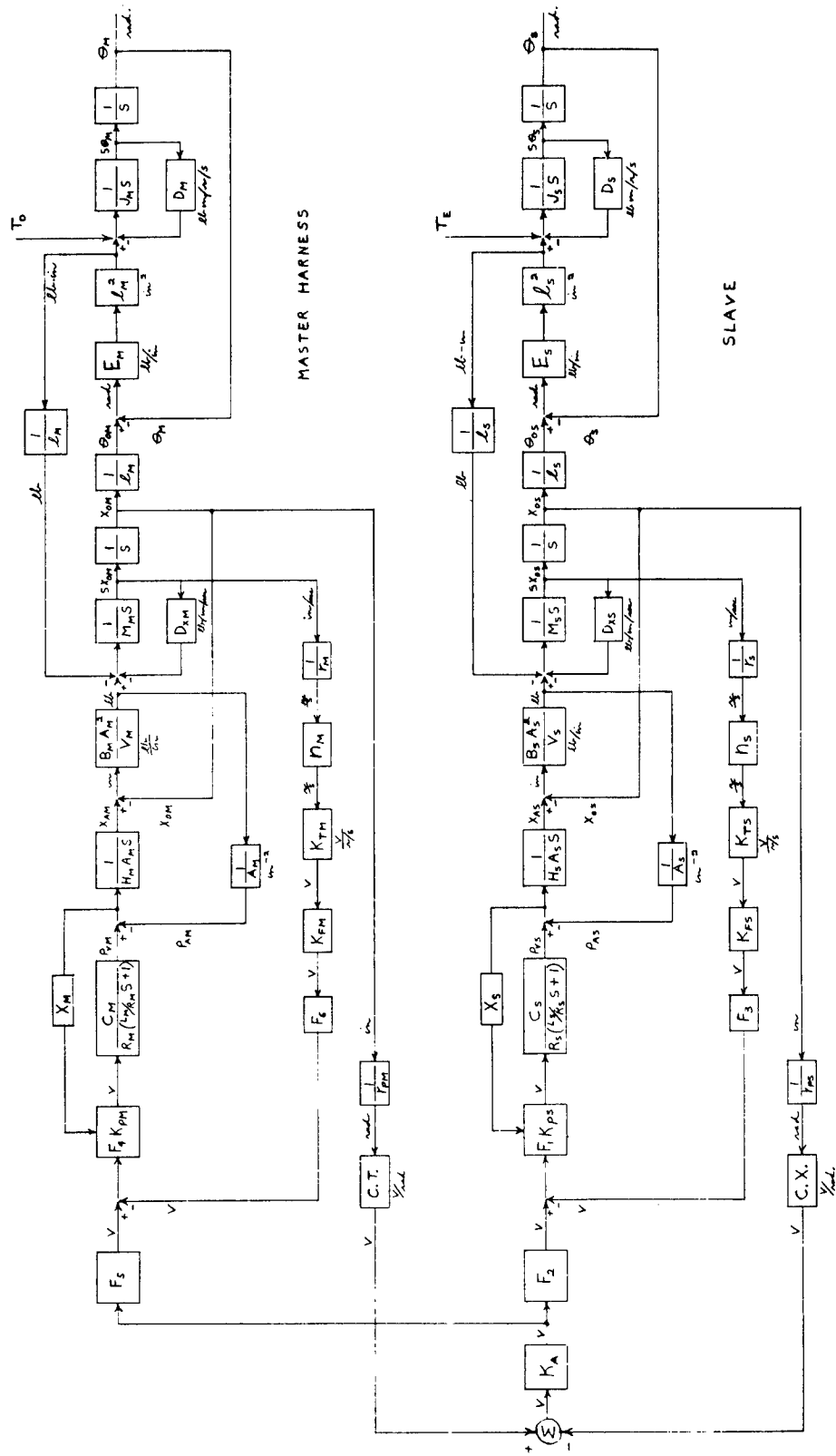
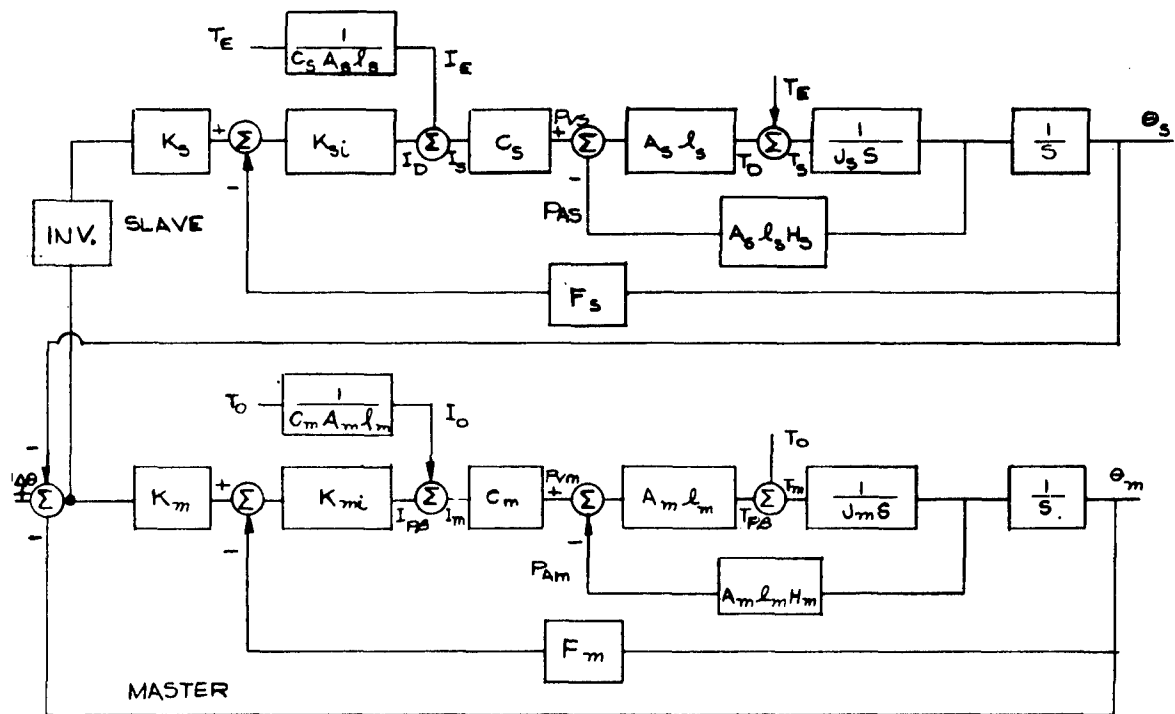
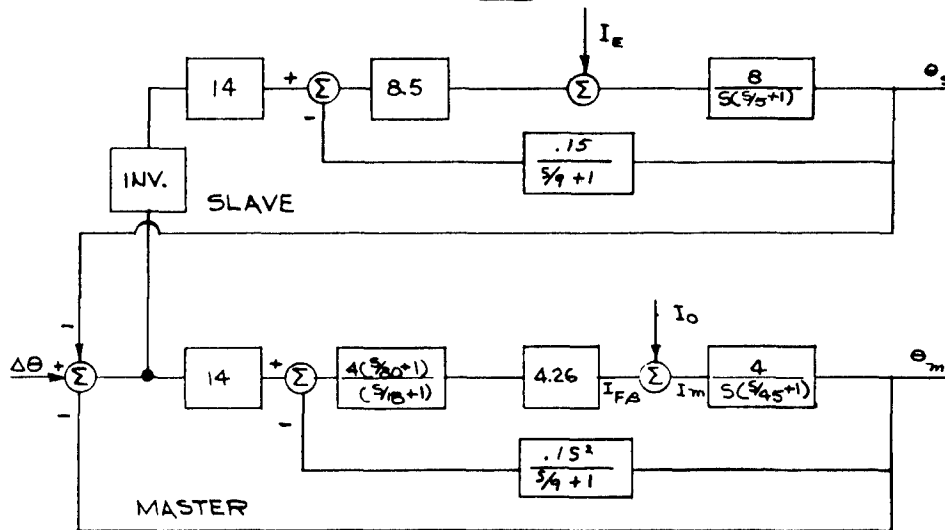


Figure 71: Bilateral Servo Symbolic Diagram



"A"



"B"

$$\frac{\theta}{P_v} = \frac{C/A_e H}{\left( \frac{J}{H A^2 L^2} S + 1 \right) S}$$

Figure 72: Bilateral Servo Computer Block Diagram

## CONTROL SYSTEM GLOSSARY OF TERMS

1. Subscripts:  $m$  denotes master  
 $s$  denotes slave  
  
no subscript denotes a general quantity that can be either master or slave
2.  $G$  = position open loop transfer function
3.  $\theta$  = angle
4.  $E$  = error signal
5.  $\Delta\theta$  = input simulating an angular displacement
6.  $J$  = inertia
7.  $T_E$  = slave external torque
8.  $T_D$  = slave drive torque
9.  $T_S$  = difference between external and drive torque that produces angular motion
10.  $T_O$  = torque applied by operator
11.  $T_{FB}$  = feedback torque applied to the operator via the harness  
whenever the master and slave are not in exact correspondence
12.  $T_M$  = difference between operator and feedback torque that produces angular motion
13.  $I$  = current necessary to produce a given amount of torque
14.  $C$  = valve pressure to current gain
15.  $H$  = hydraulic droop
16.  $A$  = actuator area
17.  $l$  = effective torque producing lever arm distance between the actuator and the load

Control System Glossary of Terms (cont.)

- 18.  $S$  = derivative notation in Laplace form
- 19.  $K$  = outer position loop electronic gain
- 20.  $K_i$  = forward inner loop electronic gain
- 21.  $F$  = tachometer feedback loop
- 22.  $P_v$  = pressure delivered by valve
- 23.  $P_A$  = pressure drop due to hydraulic droop
- 24.  $M$  = actuator mass
- 25.  $D$  = load damping torque
- 26.  $D_x$  = actuator damping torque
- 27.  $B$  = hydraulic bulk modulus
- 28.  $V$  = volume of entrained oil
- 29. C.X. = synchro control transmitter
- 30. C.T. = synchro control transformer
- 31.  $R$  = valve coil plus drive amplifier output resistance
- 32.  $L$  = valve coil inductance
- 33.  $K_A$  = A-C amplifier
- 34.  $K_p$  = D-C drive amplifier
- 35.  $F_2, F_5$  = demodulator and compensation circuits
- 36.  $F_3, F_6$  = tach. loop demodulator and compensation circuits
- 37.  $F_1, F_4$  = compensation circuits
- 38.  $r_p$  = position loop linear to angular conversion ratio
- 39.  $r$  = tachometer loop linear to angular conversion ratio
- 40.  $n$  = gear train ratio
- 41.  $K_T$  = tachometer transfer function

Control System Glossary of Terms (cont.)

- 42.  $K_F$  = tachometer loop A-C amplifier
- 43.  $E$  = mechanical compliance co-efficient
- 44.  $X$  = pressure transducer and drift compensation circuit

thus tending to make the control system unstable. Another factor that readily affects stability is component inertia and system damping. Higher inertia has the effect of decreasing the effective damping and lowering the natural frequency of the system.

Because bilateral servos are usually Type 1, it was shown that to achieve finite displacement, the operator is required to apply a force (torque), to counteract external forces applied. This feature is necessary to achieve the bilateral effect. A vehicle power steering system is one of the simplest examples of this type of control. In order to achieve finite wheel position, the driver must maintain a force to counteract the steering forces. It is interesting to note that stability is achieved primarily through the allowance of an extensive amount of hydraulic leakage around the servo valve spool when the servo is in a null or zero motion situation. This is a very ingenious arrangement where leakage not only increases stability but also is a low pressure outlet for the hydraulic pump. This results in very low power consumption when the pump is operating at high speed.

There are a multitude of design considerations which must be made when designing bilateral servos. The factors which degrade operator performance are:

- (1) Position resolution
- (2) Backlash
- (3) Hysteresis
- (4) Viscous drag and friction
- (5) Deadweight force drift
- (6) Force or torque sensitivity
- (7) Inertia

Counterbalancing is usually done to counteract dead-weight and inertia. If the operator is to operate with a harness for example, operation of the harness cannot restrict the operator's ease of articulation. Thus, the operator should not be required to work against undesirable force factors such as drift and friction; controller elements must be counterbalanced. In brief, bilateral servo design is a complex task and requires thorough consideration of both man and machine requirements.

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## SECTION II

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